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Chen

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(54) **END-TO-END (E2E) TUNNEL BASED ON SHORTEST POINT-TO-POINT (P2P) PATH COMPUTATION**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 52 days.

(21) Appl. No.: **15/370,920**

(22) Filed: **Dec. 6, 2016**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**

H04L 12/46 (2006.01)
H04L 12/721 (2013.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H04L 12/4633*** (2013.01); ***H04L 45/124*** (2013.01); *H04L 45/04* (2013.01); *H04L 45/48* (2013.01)

(58) **Field of Classification Search**

CPC H04L 45/12; H04L 45/04; H04L 45/48; H04L 45/124; H04L 12/4633; H04L 12/273; H04L 12/759

See application file for complete search history.

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(Continued)

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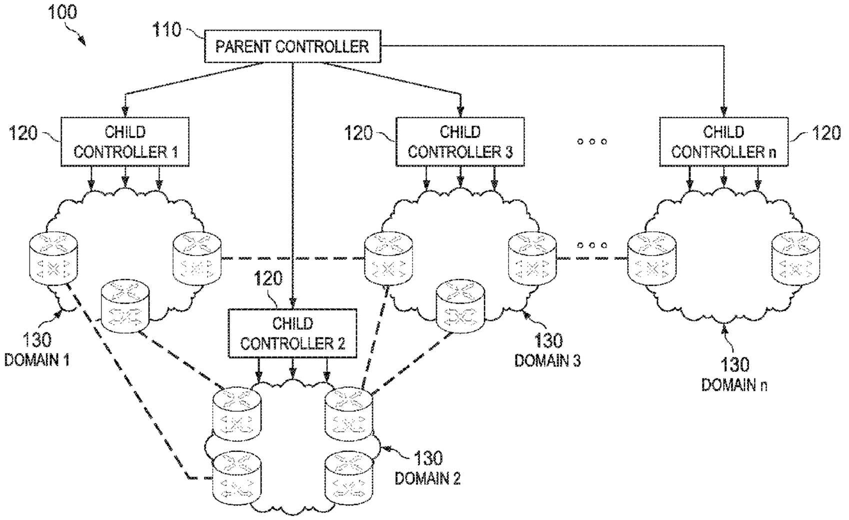
(57) **ABSTRACT**

A method implemented in a parent controller including receiving a request to compute a shortest end-to-end (E2E) path from source to destination through network domains managed by child controllers, receiving path segments and costs computed by the child controllers, wherein the path segments identify in-edge nodes, out-edge nodes, and inter-domain links, generating a candidate list using the path segments and costs received from the child controllers, constructing a shortest path tree (SPT) from the source to the destination through the network domains by repeatedly removing one of the out-edge nodes corresponding to the path segment in the candidate list having a lowest cost and adding the one of the out-edge nodes to the SPT until the destination is reached, determining the shortest E2E path based on the SPT, and transmitting tunnel creation messages to the child controllers to create a tunnel along the shortest E2E path.

20 Claims, 21 Drawing Sheets



(51) **Int. Cl.**

H04L 12/715	(2013.01)
H04L 12/753	(2013.01)

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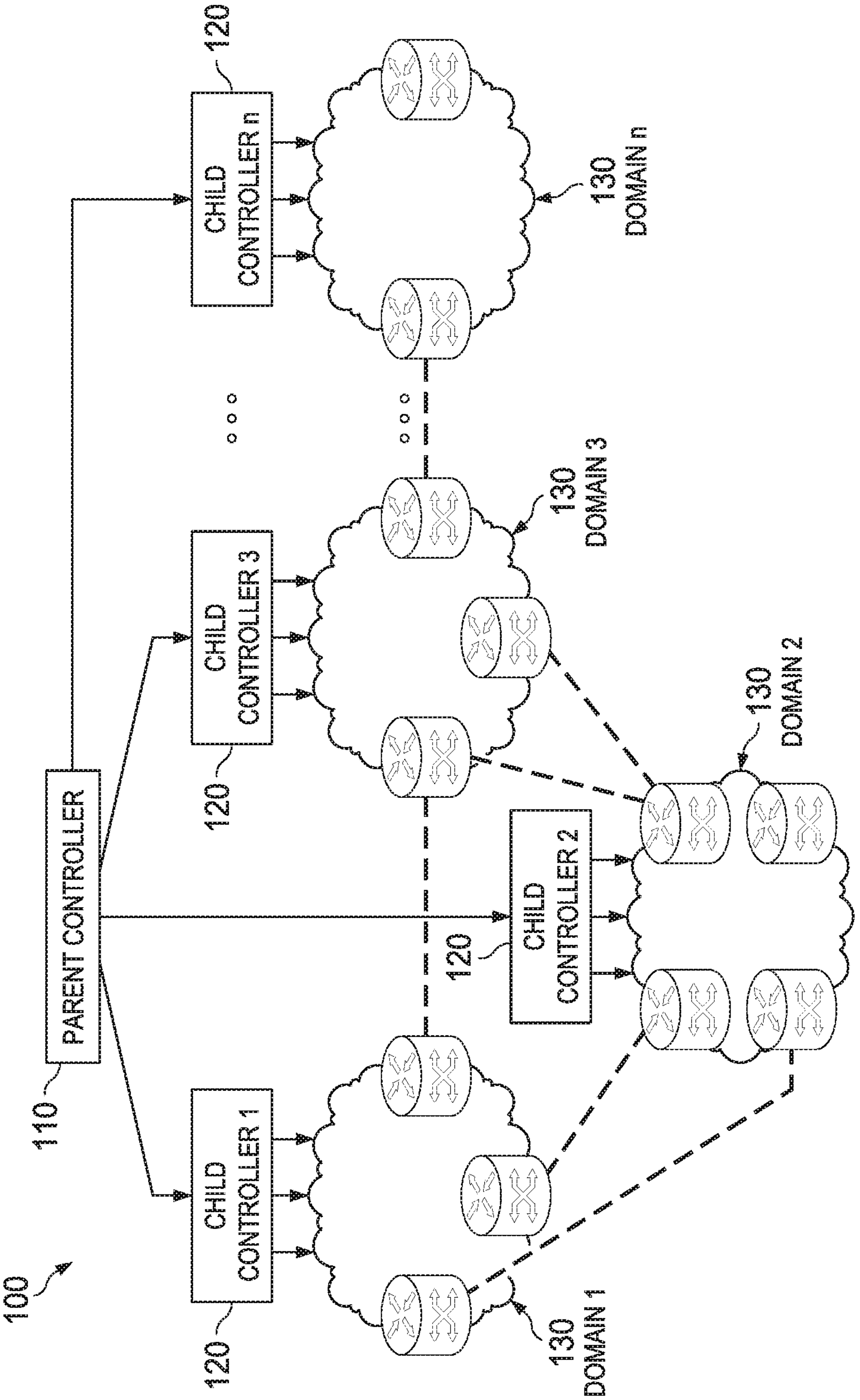
100
110
PARENT CONTROLLER
120
CHILD CONTROLLER 1
120
CHILD CONTROLLER 2
120
CHILD CONTROLLER 3
120
CHILD CONTROLLER n
130
DOMAIN 1
130
DOMAIN 2
130
DOMAIN 3
130
DOMAIN n

FIG. 1

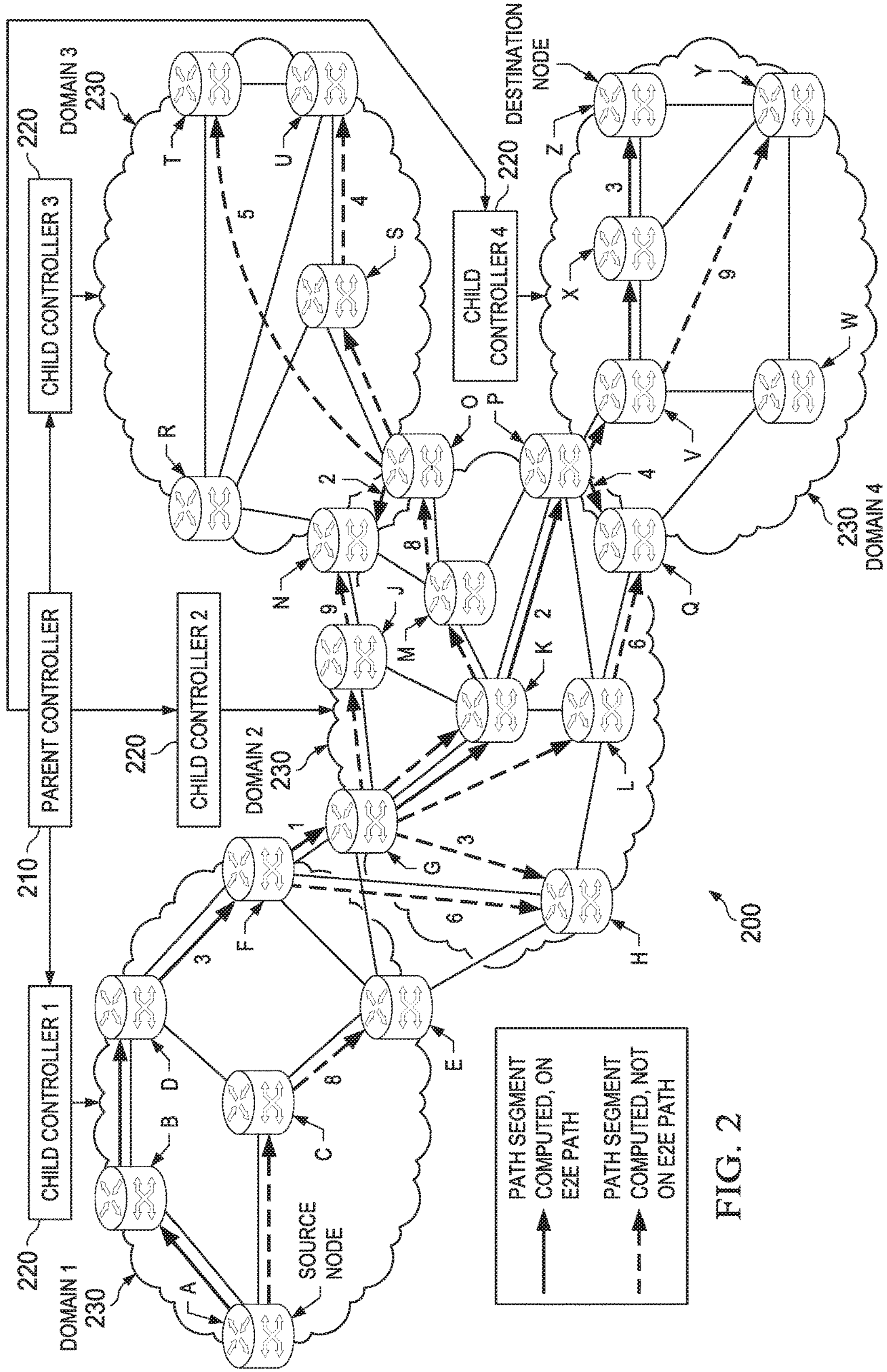
PARENT CONTROLLER
210
CHILD CONTROLLER 1
CHILD CONTROLLER 2
CHILD CONTROLLER 3
CHILD CONTROLLER 4
220
220
220
220
DOMAIN 1
230
DOMAIN 2
230
DOMAIN 3
230
DOMAIN 4
230
SOURCE NODE
DESTINATION NODE
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
1
2
3
4
5
6
8
9
PATH SEGMENT COMPUTED, ON E2E PATH
PATH SEGMENT COMPUTED, NOT ON E2E PATH
200

FIG. 2

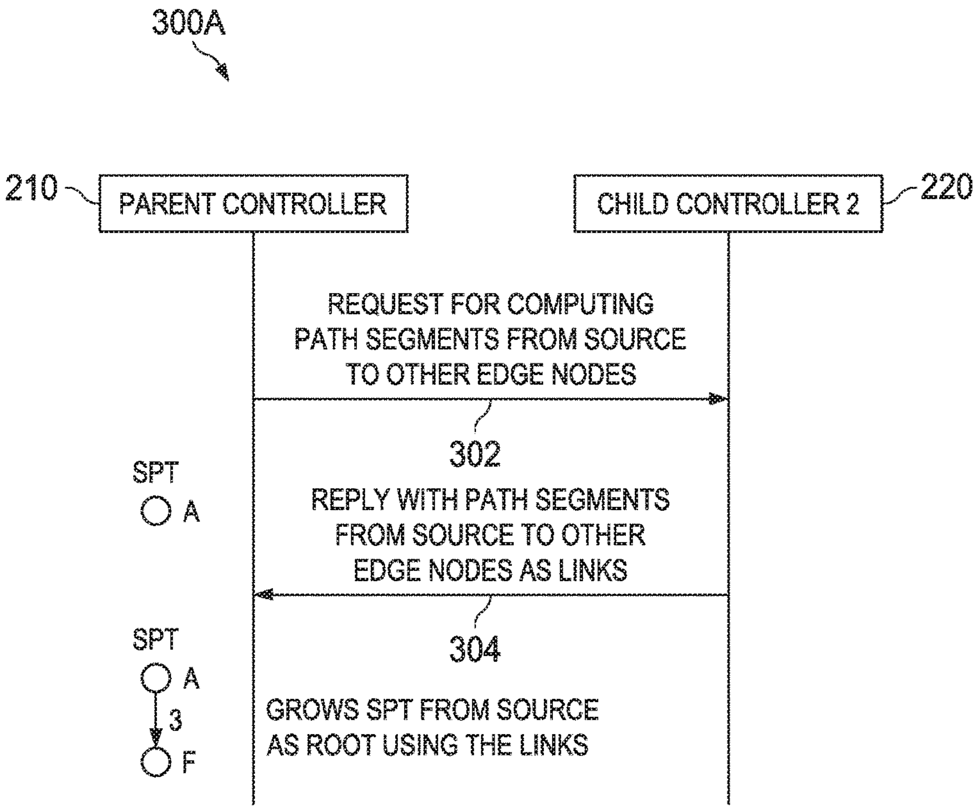
300A
210
PARENT CONTROLLER
CHILD CONTROLLER 2
220
REQUEST FOR COMPUTING PATH SEGMENTS FROM SOURCE TO OTHER EDGE NODES
302
SPT
A
REPLY WITH PATH SEGMENTS FROM SOURCE TO OTHER EDGE NODES AS LINKS
304
SPT
A
3
F
GROWS SPT FROM SOURCE AS ROOT USING THE LINKS

FIG. 3A

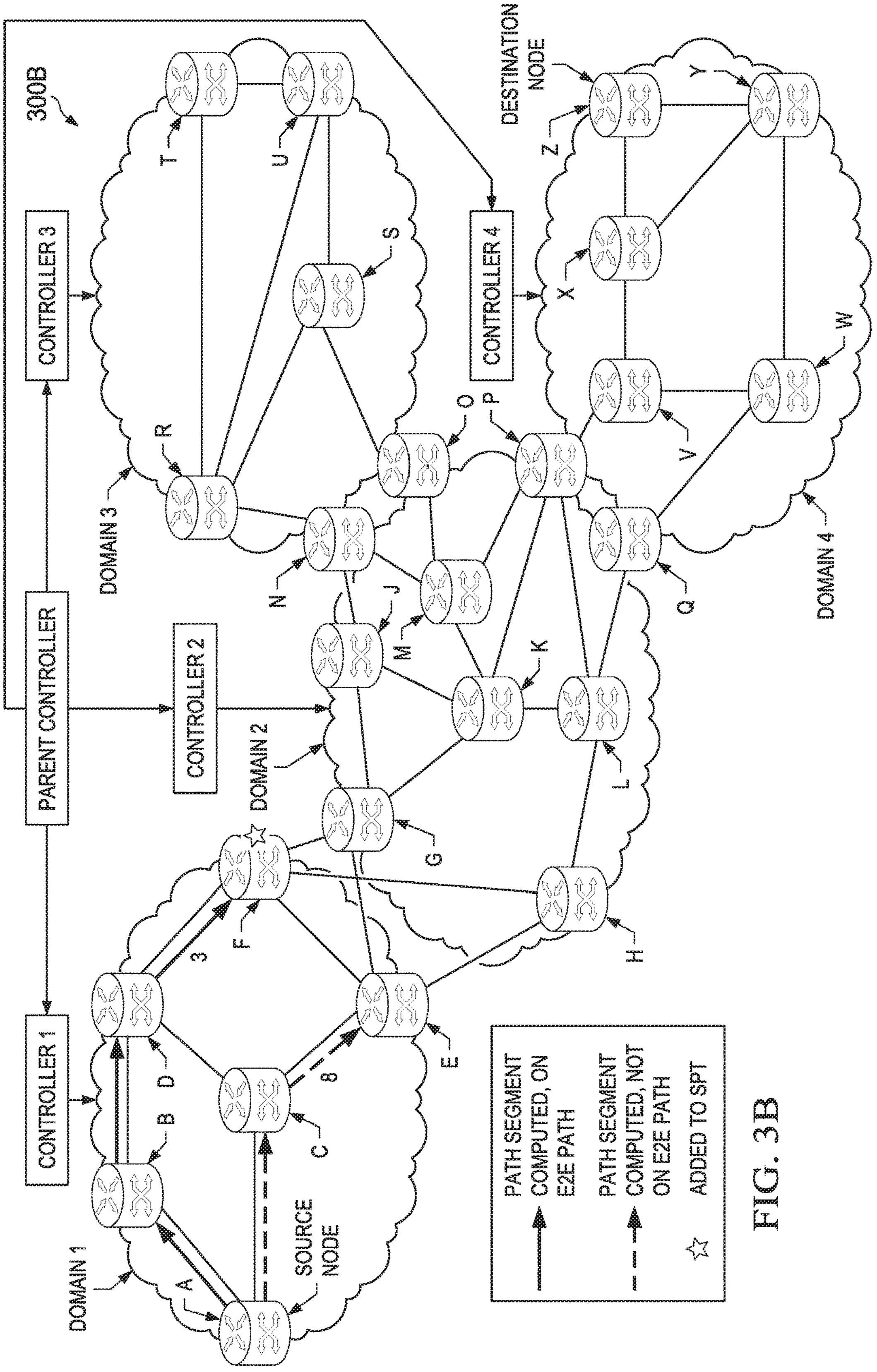
300B
PARENT CONTROLLER
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
CONTROLLER 4
DOMAIN 1
DOMAIN 2
DOMAIN 3
DOMAIN 4
SOURCE NODE
DESTINATION NODE
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
3
8
PATH SEGMENT COMPUTED, ON E2E PATH
PATH SEGMENT COMPUTED, NOT ON E2E PATH
☆ ADDED TO SPT

FIG. 3B

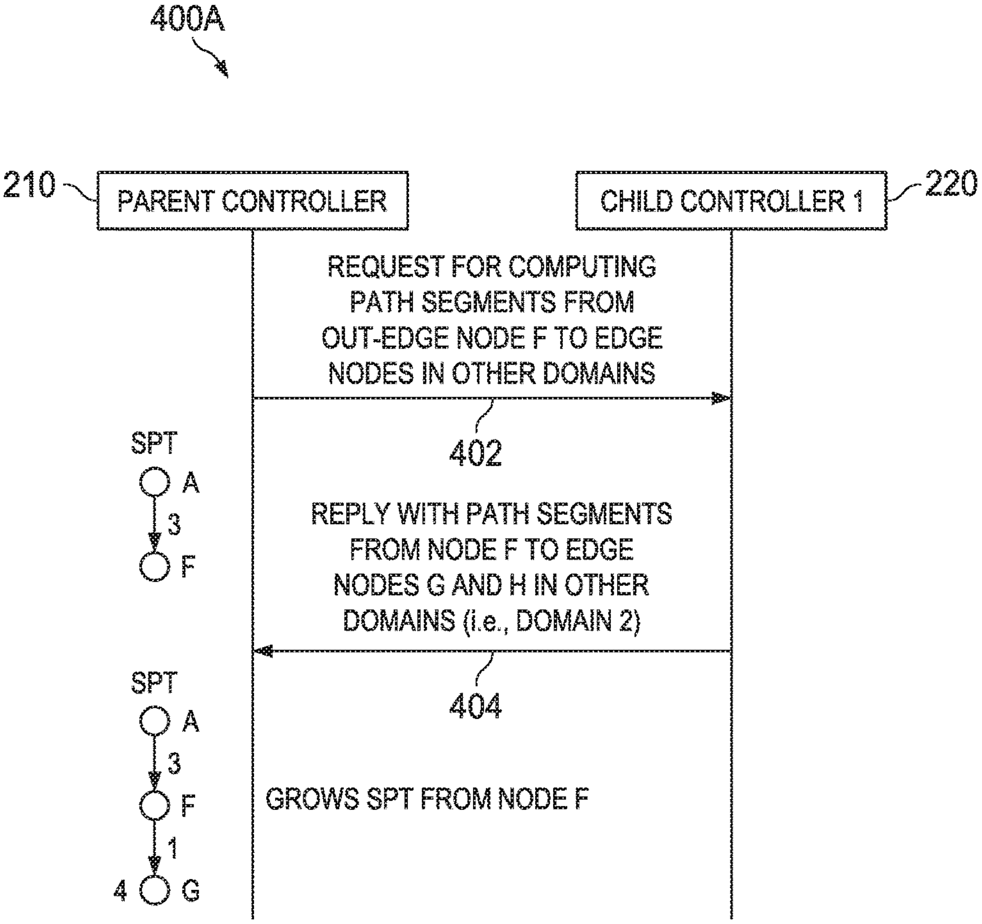
400A
210
PARENT CONTROLLER
CHILD CONTROLLER 1
220
REQUEST FOR COMPUTING PATH SEGMENTS FROM OUT-EDGE NODE F TO EDGE NODES IN OTHER DOMAINS
402
SPT
A
3
F
REPLY WITH PATH SEGMENTS FROM NODE F TO EDGE NODES G AND H IN OTHER DOMAINS (i.e., DOMAIN 2)
404
SPT
A
3
F
1
4
G
GROWS SPT FROM NODE F

FIG. 4A

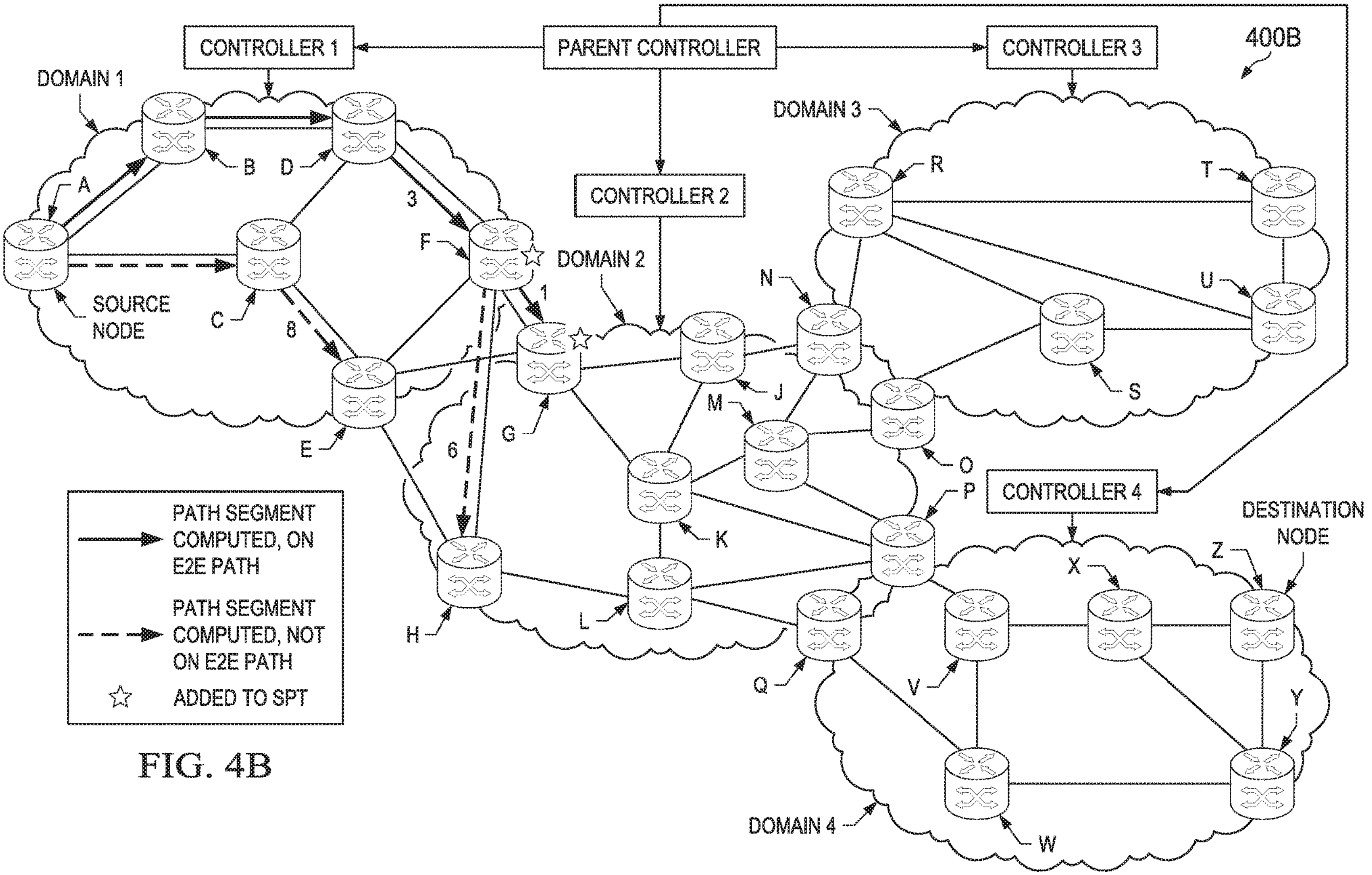
400B
PARENT CONTROLLER
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
CONTROLLER 4
DOMAIN 1
DOMAIN 2
DOMAIN 3
DOMAIN 4
SOURCE NODE
DESTINATION NODE
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
3
8
1
6
PATH SEGMENT COMPUTED, ON E2E PATH
PATH SEGMENT COMPUTED, NOT ON E2E PATH
☆ ADDED TO SPT

FIG. 4B

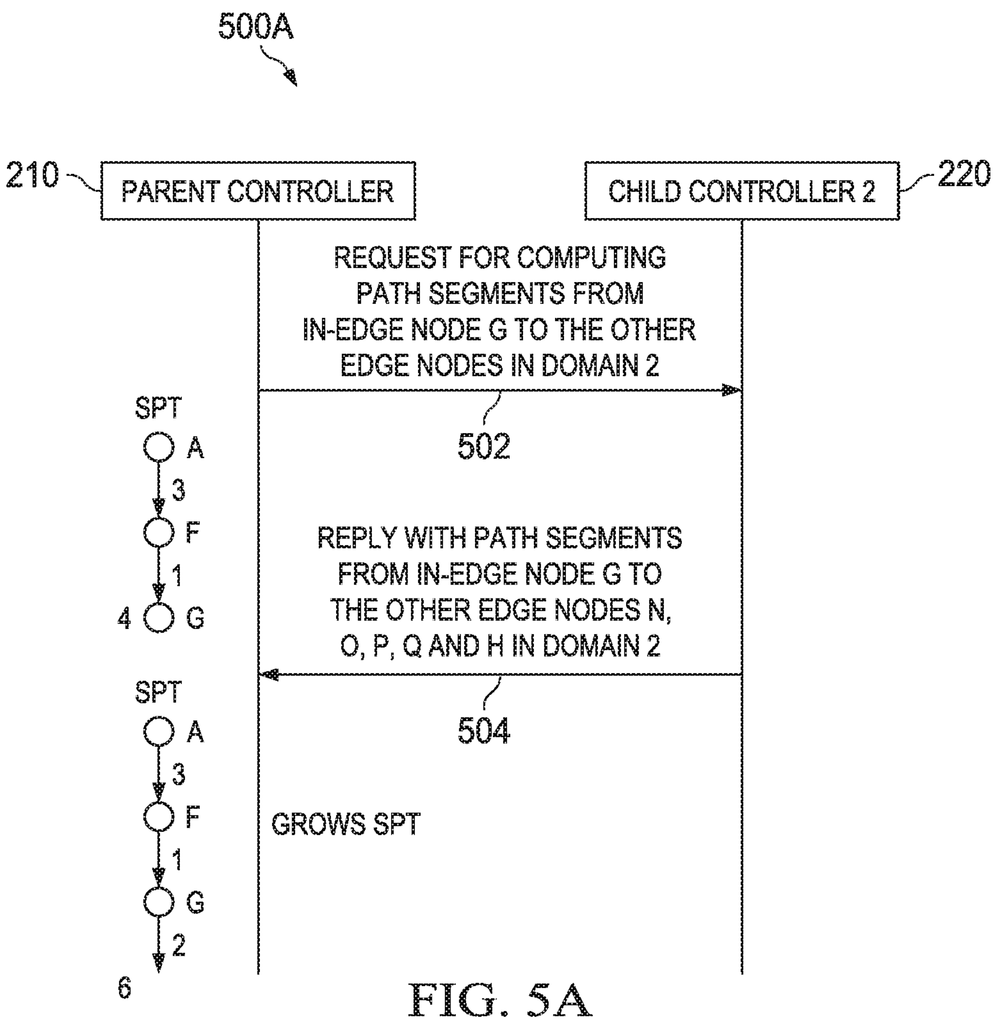
500A
210
PARENT CONTROLLER
CHILD CONTROLLER 2
220
REQUEST FOR COMPUTING PATH SEGMENTS FROM IN-EDGE NODE G TO THE OTHER EDGE NODES IN DOMAIN 2
502
SPT
A
3
F
1
4
G
REPLY WITH PATH SEGMENTS FROM IN-EDGE NODE G TO THE OTHER EDGE NODES N, O, P, Q AND H IN DOMAIN 2
504
SPT
A
3
F
GROWS SPT
1
G
2
6

FIG. 5A

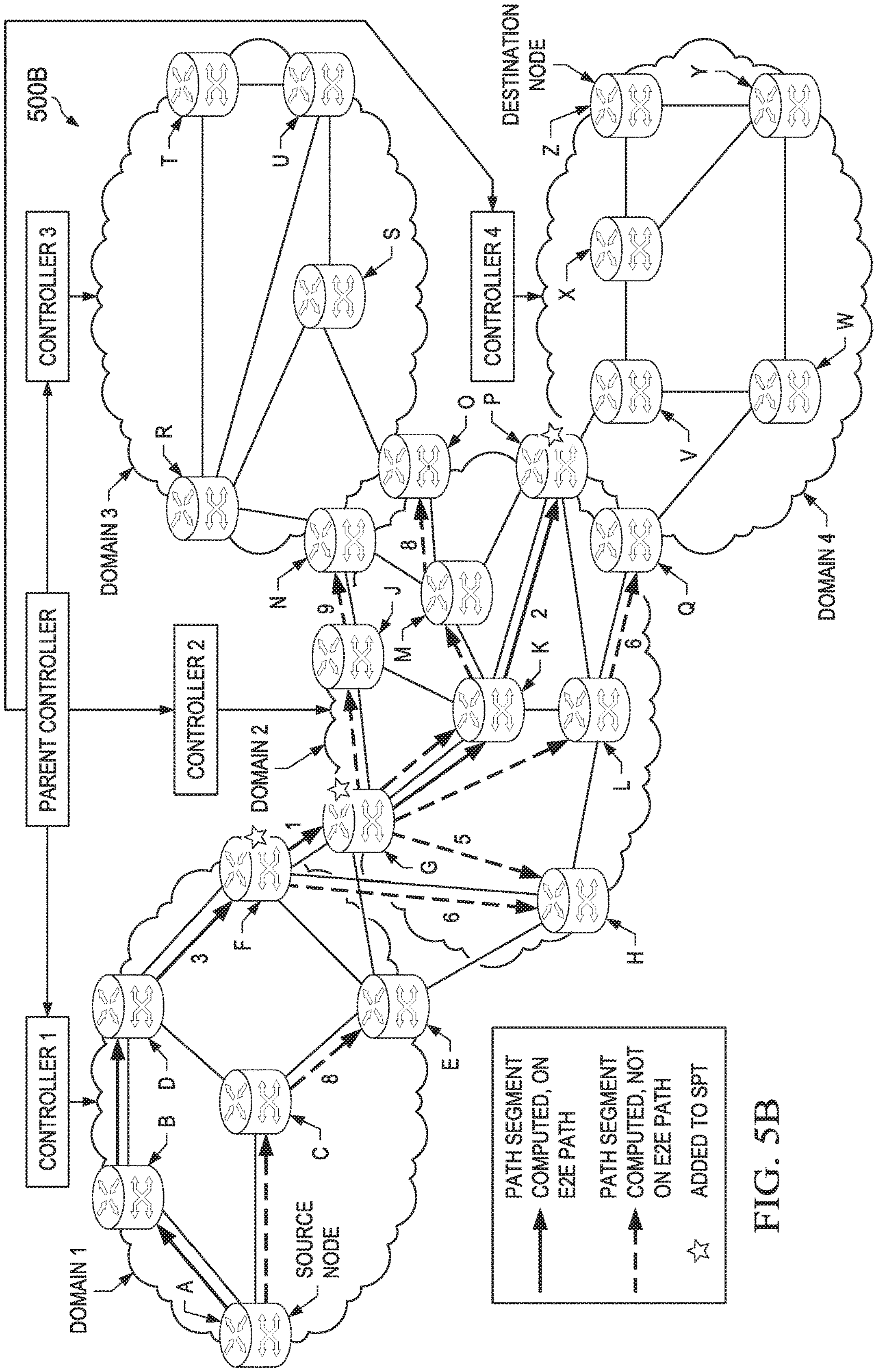
500B
PARENT CONTROLLER
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
CONTROLLER 4
DOMAIN 1
DOMAIN 2
DOMAIN 3
DOMAIN 4
SOURCE NODE
DESTINATION NODE
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
1
2
3
5
6
6
6
8
8
9
PATH SEGMENT COMPUTED, ON E2E PATH
PATH SEGMENT COMPUTED, NOT ON E2E PATH
☆ ADDED TO SPT

FIG. 5B

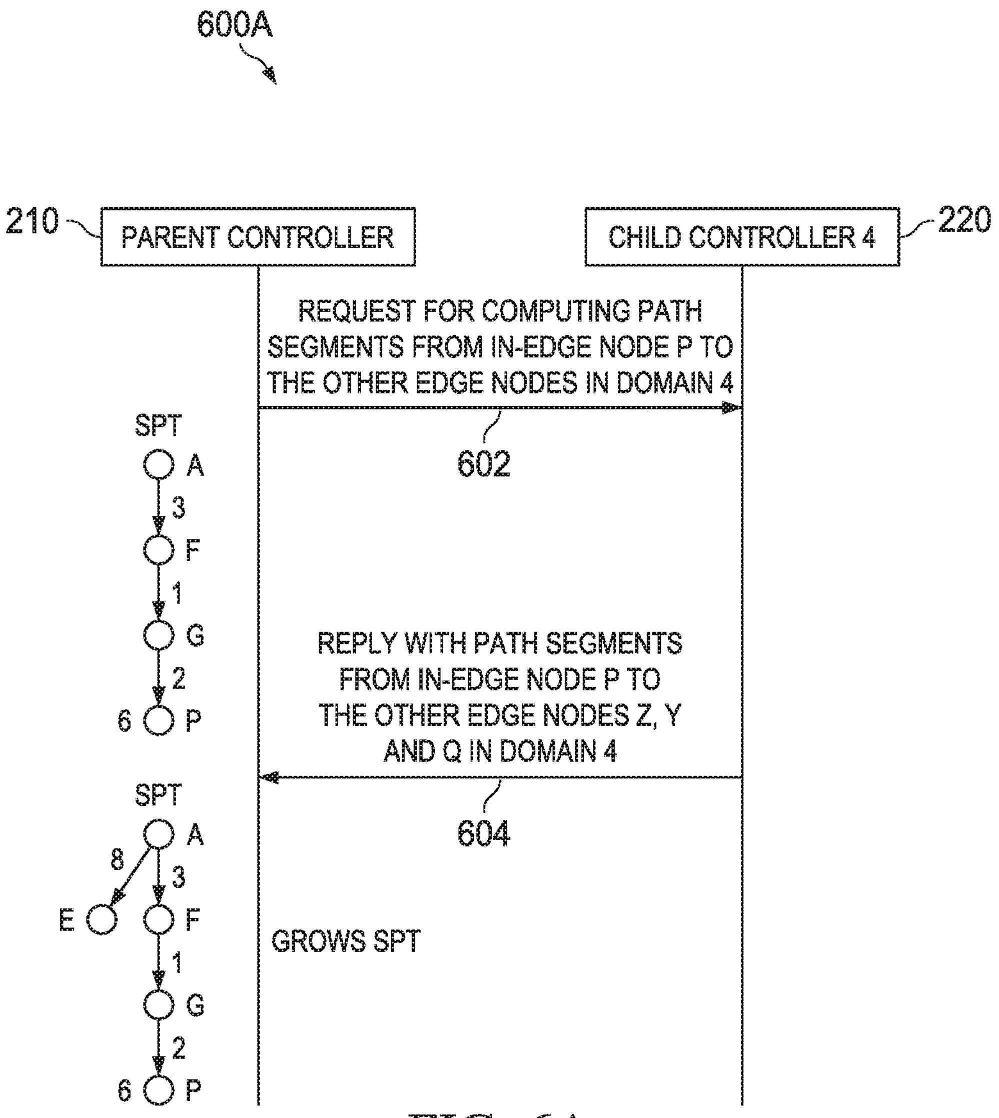
600A
210
PARENT CONTROLLER
CHILD CONTROLLER 4
220
REQUEST FOR COMPUTING PATH SEGMENTS FROM IN-EDGE NODE P TO THE OTHER EDGE NODES IN DOMAIN 4
602
SPT
A
3
F
1
G
2
6
P
REPLY WITH PATH SEGMENTS FROM IN-EDGE NODE P TO THE OTHER EDGE NODES Z, Y AND Q IN DOMAIN 4
604
SPT
A
8
3
E
F
GROWS SPT
1
G
2
6
P

FIG. 6A

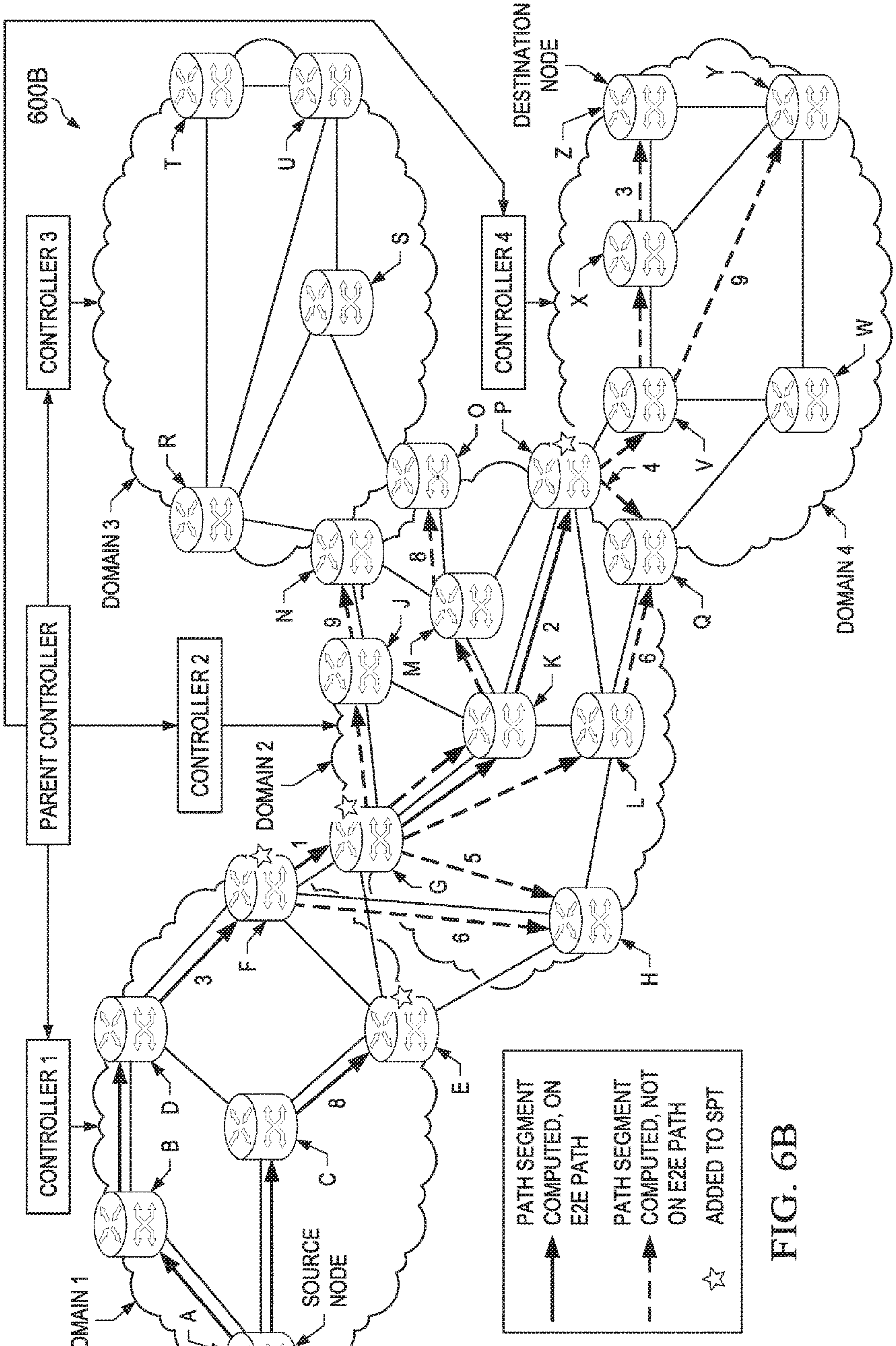
600B
PARENT CONTROLLER
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
CONTROLLER 4
DOMAIN 1
DOMAIN 2
DOMAIN 3
DOMAIN 4
SOURCE NODE
DESTINATION NODE
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
8
3
1
6
5
9
2
6
8
4
9
3
PATH SEGMENT COMPUTED, ON E2E PATH
PATH SEGMENT COMPUTED, NOT ON E2E PATH
ADDED TO SPT

FIG. 6B

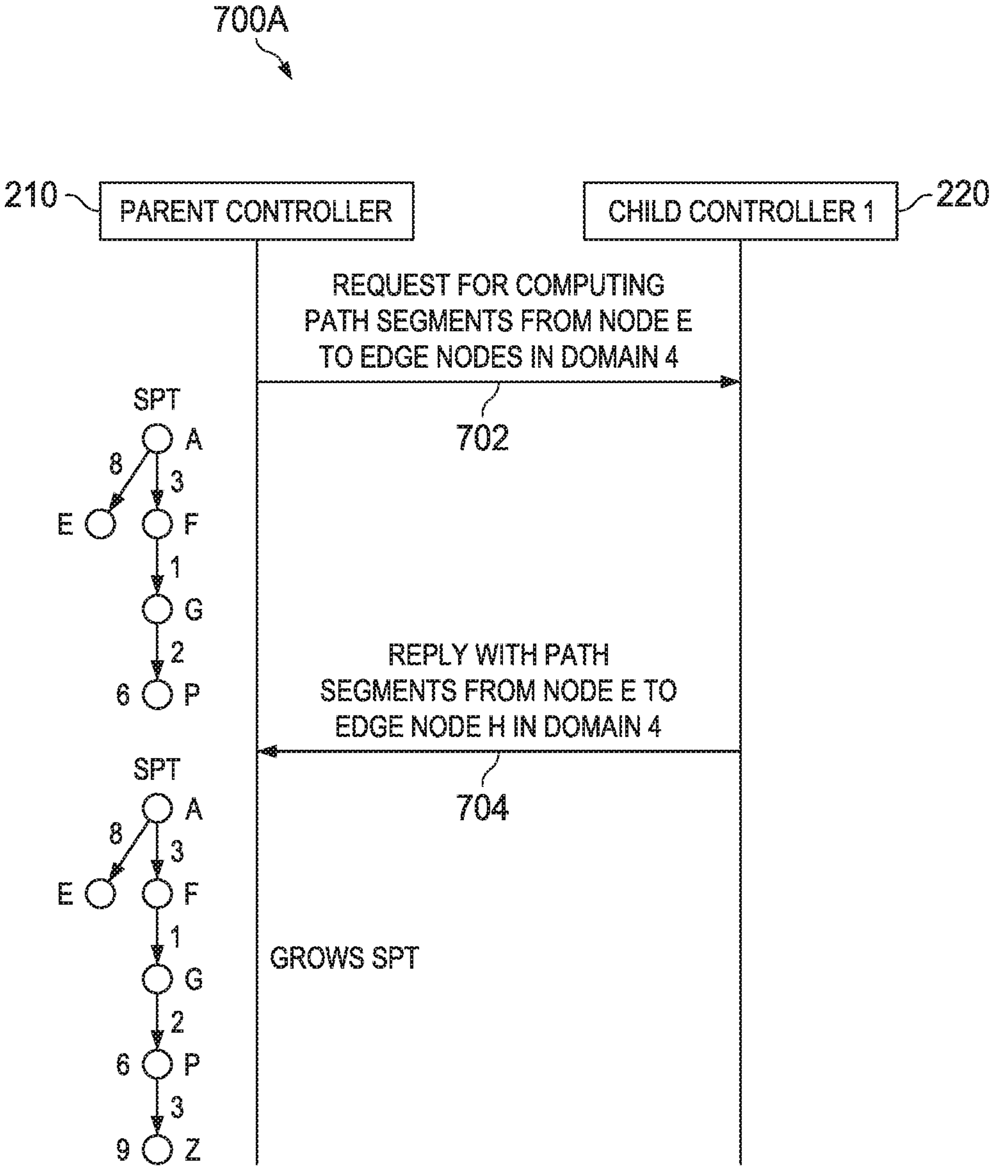
700A
210
PARENT CONTROLLER
CHILD CONTROLLER 1
220
REQUEST FOR COMPUTING PATH SEGMENTS FROM NODE E TO EDGE NODES IN DOMAIN 4
702
SPT
A
8
3
E
F
1
G
2
6
P
REPLY WITH PATH SEGMENTS FROM NODE E TO EDGE NODE H IN DOMAIN 4
704
SPT
A
8
3
E
F
1
G
GROWS SPT
2
6
P
3
9
Z

FIG. 7A

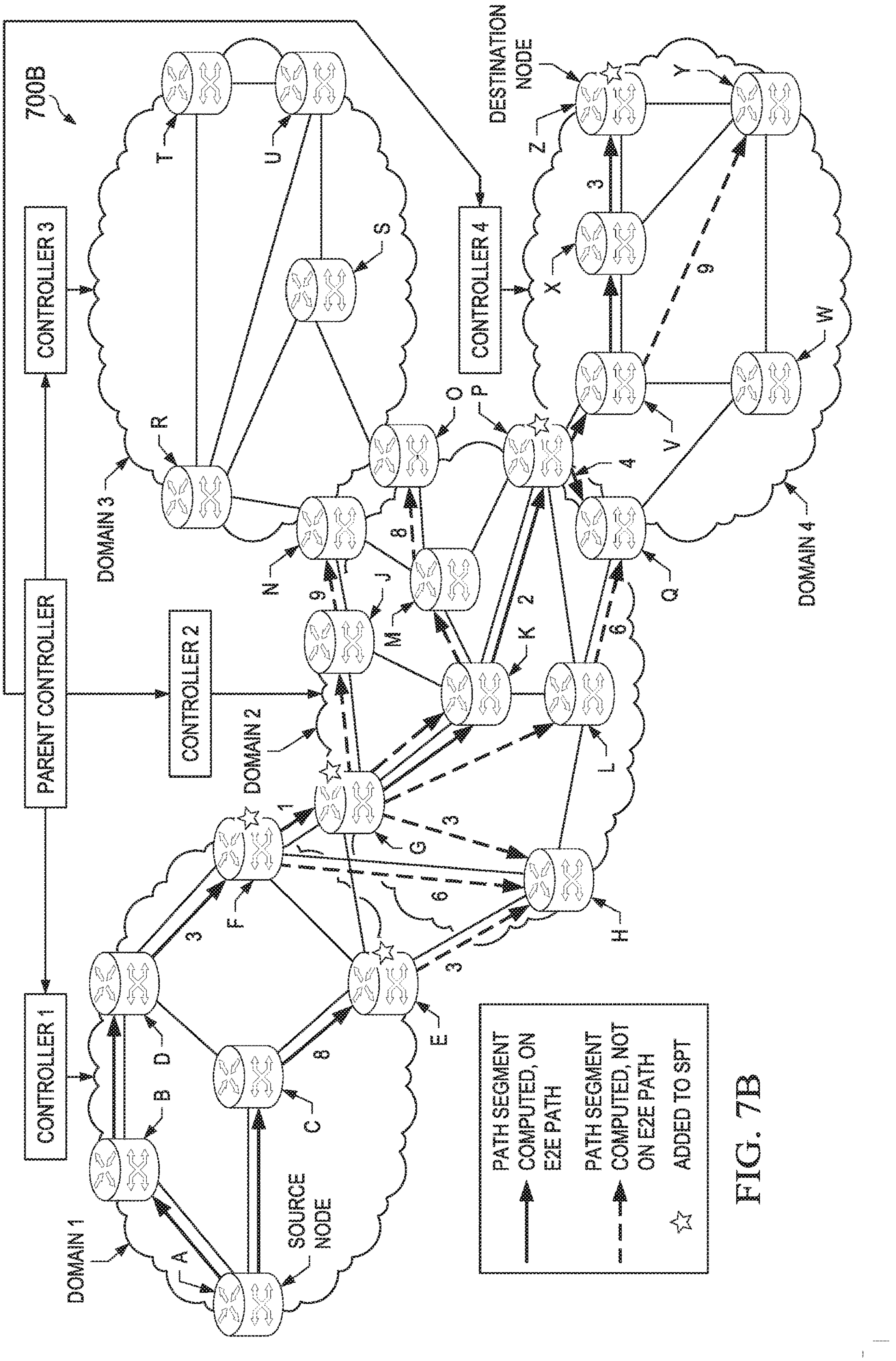
700B
PARENT CONTROLLER
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
CONTROLLER 4
DOMAIN 1
DOMAIN 2
DOMAIN 3
DOMAIN 4
SOURCE NODE
DESTINATION NODE
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
3
8
1
6
3
3
9
2
6
8
4
3
9
PATH SEGMENT COMPUTED, ON E2E PATH
PATH SEGMENT COMPUTED, NOT ON E2E PATH
ADDED TO SPT

FIG. 7B

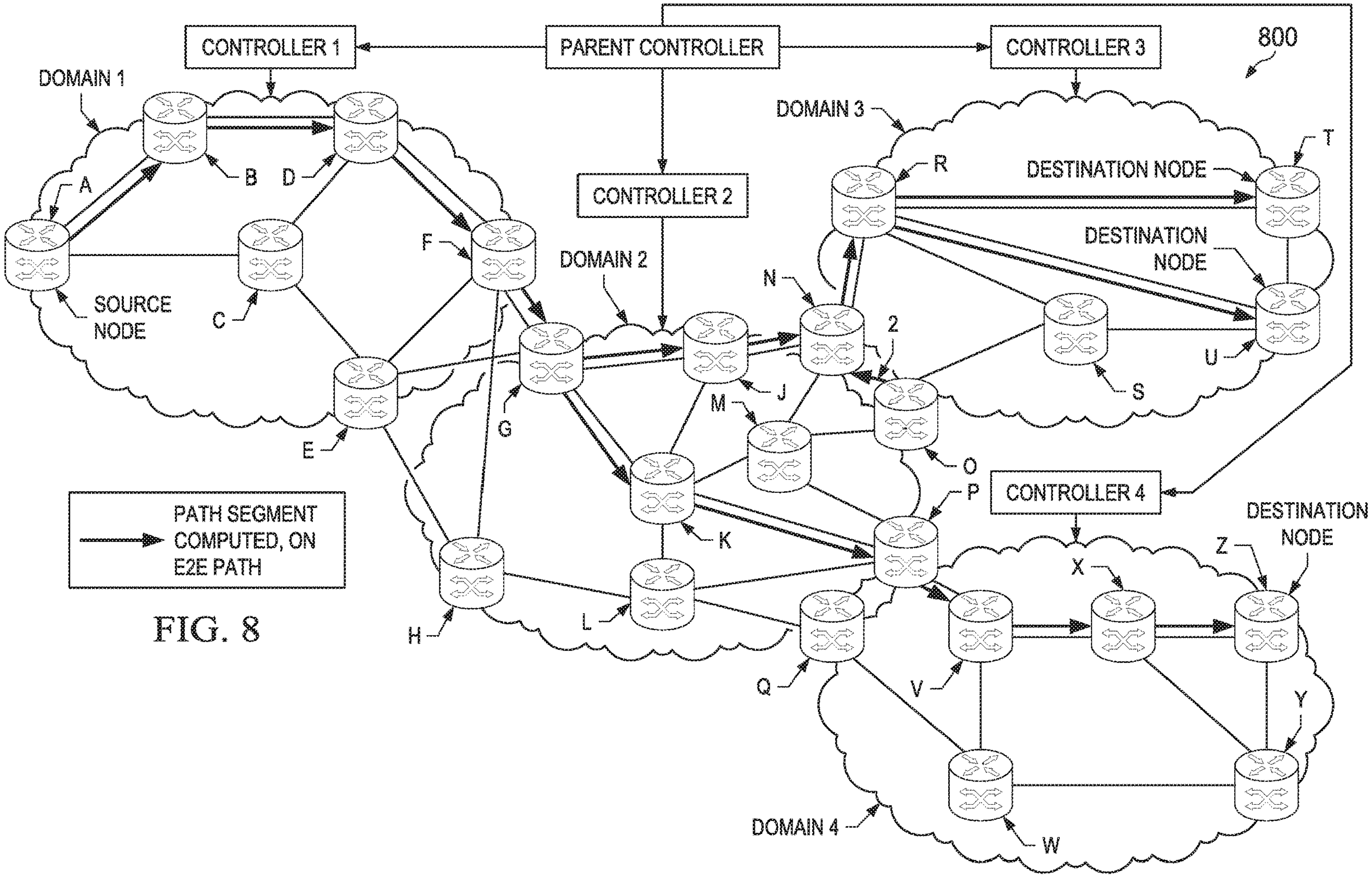
800
CONTROLLER 1
PARENT CONTROLLER
CONTROLLER 3
CONTROLLER 2
CONTROLLER 4
DOMAIN 1
DOMAIN 2
DOMAIN 3
DOMAIN 4
A
B
C
D
E
F
G
H
J
K
L
M
N
2
O
P
Q
R
S
T
U
V
W
X
Y
Z
SOURCE NODE
DESTINATION NODE
DESTINATION NODE
DESTINATION NODE
PATH SEGMENT COMPUTED, ON E2E PATH

FIG. 8

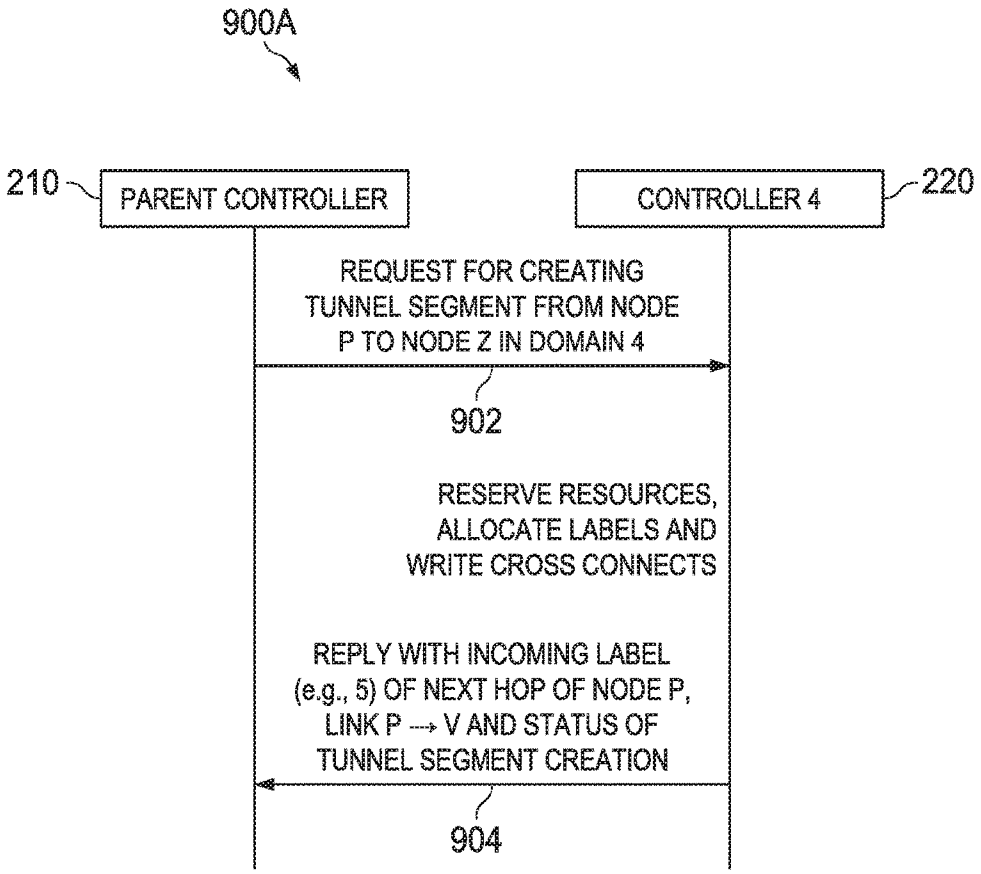
900A
210
PARENT CONTROLLER
CONTROLLER 4
220
REQUEST FOR CREATING TUNNEL SEGMENT FROM NODE P TO NODE Z IN DOMAIN 4
902
RESERVE RESOURCES, ALLOCATE LABELS AND WRITE CROSS CONNECTS
REPLY WITH INCOMING LABEL (e.g., 5) OF NEXT HOP OF NODE P, LINK P → V AND STATUS OF TUNNEL SEGMENT CREATION
904

FIG. 9A

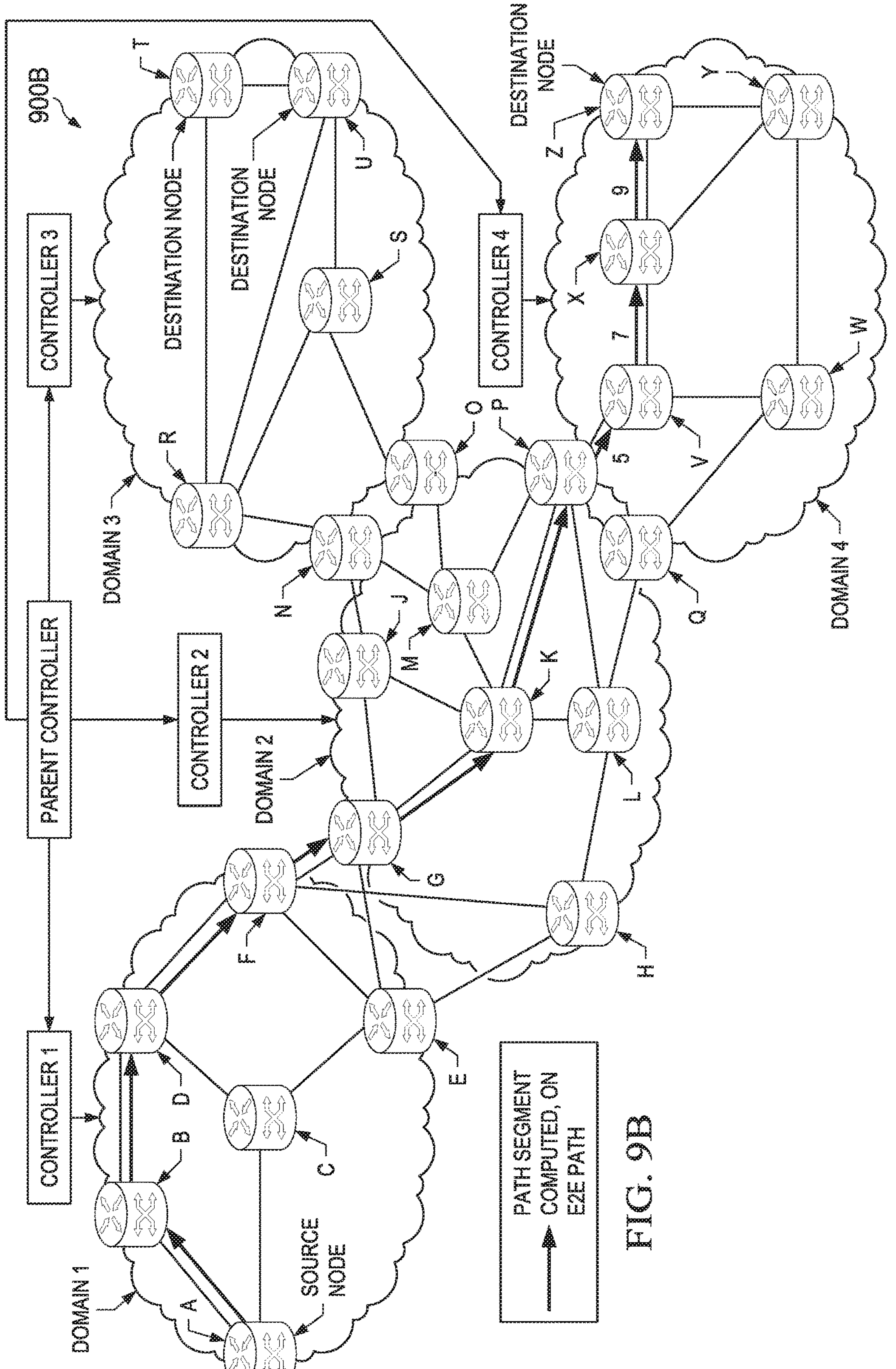
900B
PARENT CONTROLLER
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
CONTROLLER 4
DOMAIN 1
DOMAIN 2
DOMAIN 3
DOMAIN 4
SOURCE NODE
DESTINATION NODE
DESTINATION NODE
DESTINATION NODE
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
5
7
9
PATH SEGMENT COMPUTED, ON E2E PATH

FIG. 9B

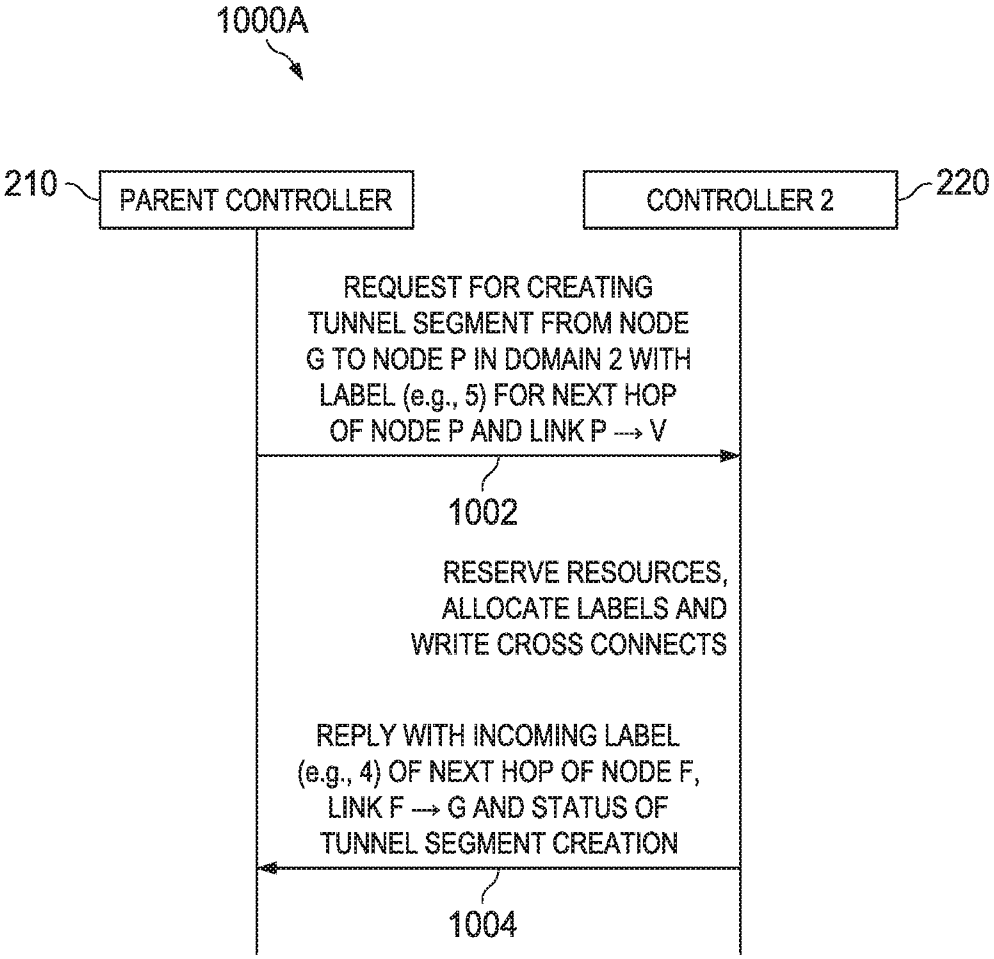
1000A
210
PARENT CONTROLLER
CONTROLLER 2
220
REQUEST FOR CREATING TUNNEL SEGMENT FROM NODE G TO NODE P IN DOMAIN 2 WITH LABEL (e.g., 5) FOR NEXT HOP OF NODE P AND LINK P → V
1002
RESERVE RESOURCES, ALLOCATE LABELS AND WRITE CROSS CONNECTS
REPLY WITH INCOMING LABEL (e.g., 4) OF NEXT HOP OF NODE F, LINK F → G AND STATUS OF TUNNEL SEGMENT CREATION
1004

FIG. 10A

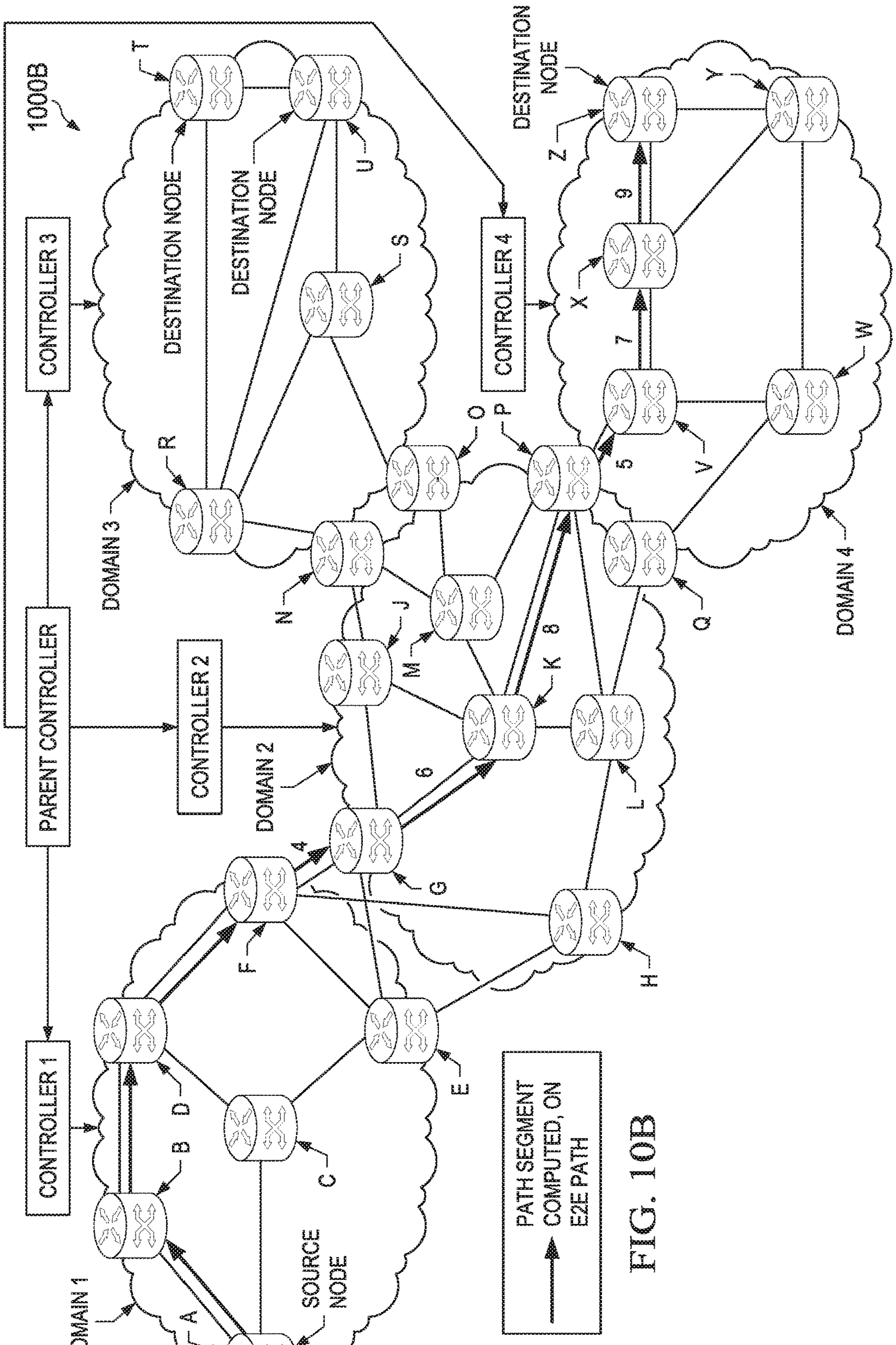
1000B
PARENT CONTROLLER
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
CONTROLLER 4
DOMAIN 1
DOMAIN 2
DOMAIN 3
DOMAIN 4
SOURCE NODE
DESTINATION NODE
DESTINATION NODE
DESTINATION NODE
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
4
5
6
7
8
9
PATH SEGMENT COMPUTED, ON E2E PATH

FIG. 10B

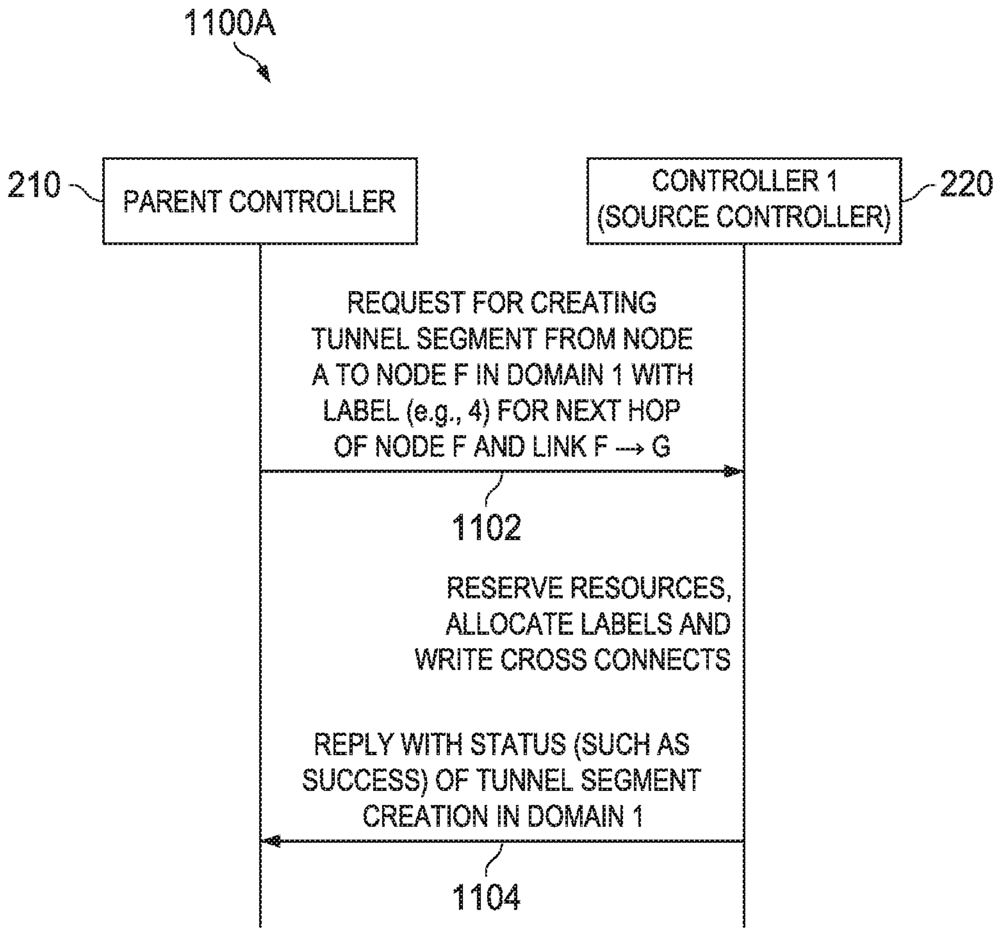
1100A
210
PARENT CONTROLLER
CONTROLLER 1
(SOURCE CONTROLLER)
220
REQUEST FOR CREATING
TUNNEL SEGMENT FROM NODE
A TO NODE F IN DOMAIN 1 WITH
LABEL (e.g., 4) FOR NEXT HOP
OF NODE F AND LINK F → G
1102
RESERVE RESOURCES,
ALLOCATE LABELS AND
WRITE CROSS CONNECTS
REPLY WITH STATUS (SUCH AS
SUCCESS) OF TUNNEL SEGMENT
CREATION IN DOMAIN 1
1104

FIG. 11A

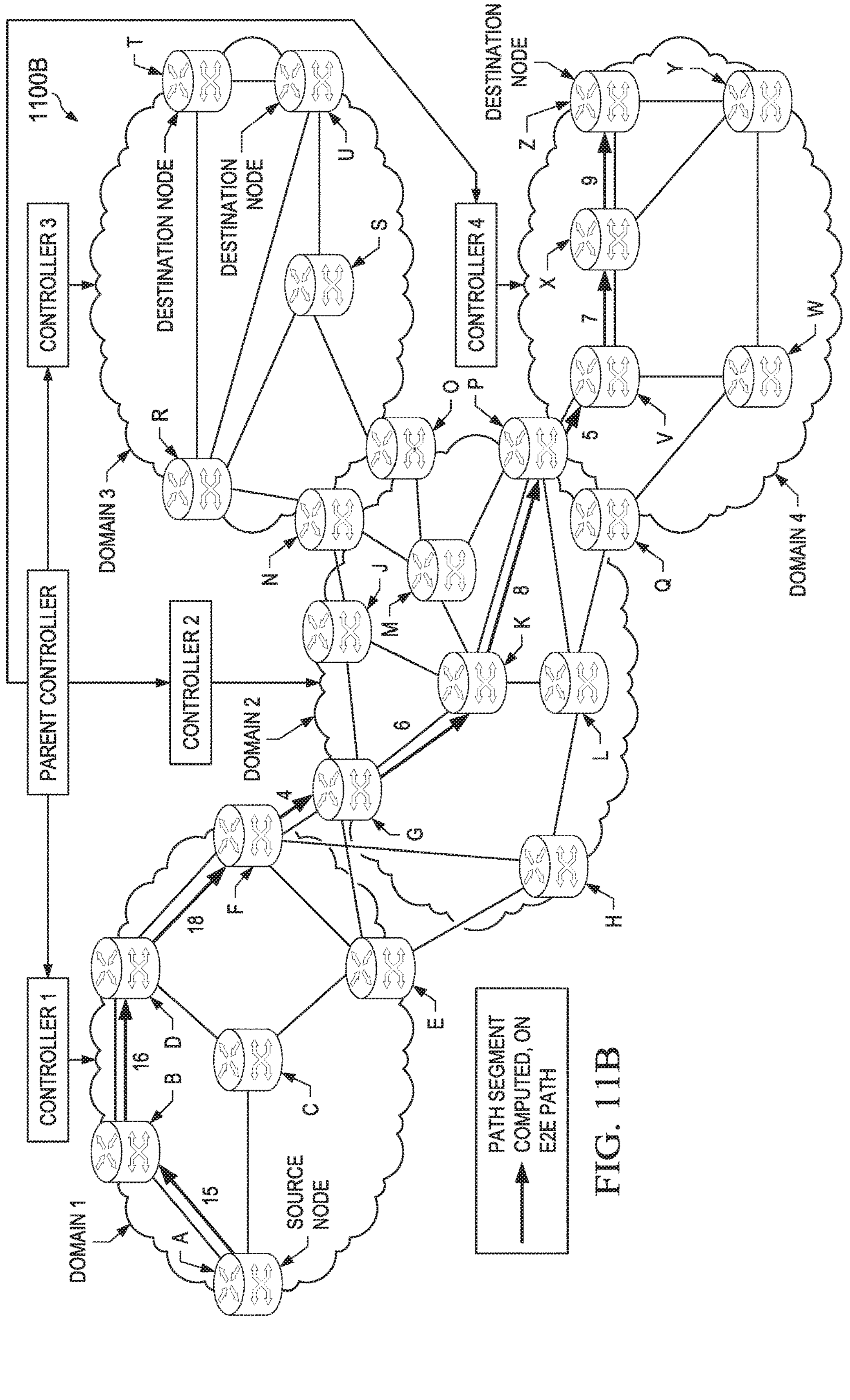
1100B
PARENT CONTROLLER
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
CONTROLLER 4
DOMAIN 1
DOMAIN 2
DOMAIN 3
DOMAIN 4
SOURCE NODE
DESTINATION NODE
DESTINATION NODE
DESTINATION NODE
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
15
16
18
4
6
8
5
7
9
PATH SEGMENT COMPUTED, ON E2E PATH

FIG. 11B

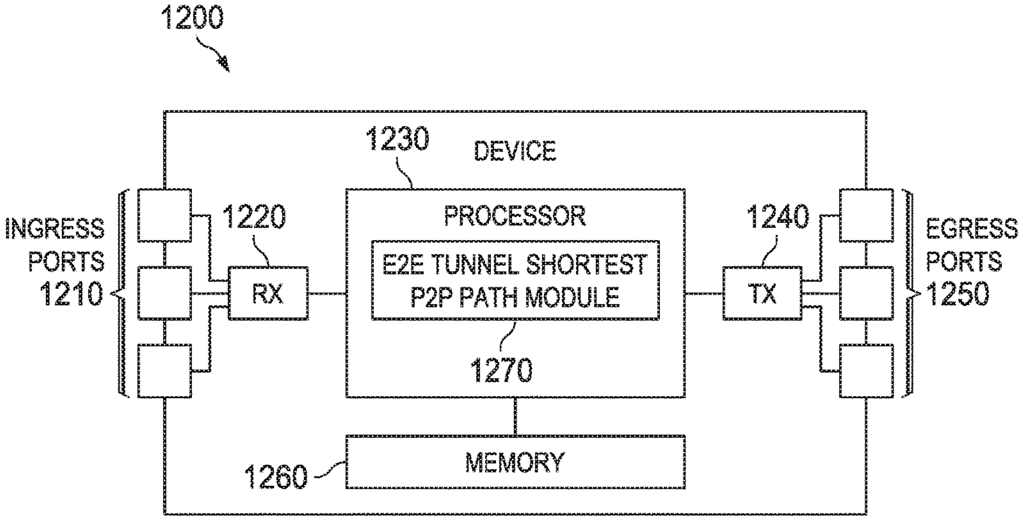
1200
1230
DEVICE
PROCESSOR
INGRESS PORTS 1210
1220
RX
E2E TUNNEL SHORTEST P2P PATH MODULE
1270
1240
TX
EGRESS PORTS 1250
1260
MEMORY

FIG. 12

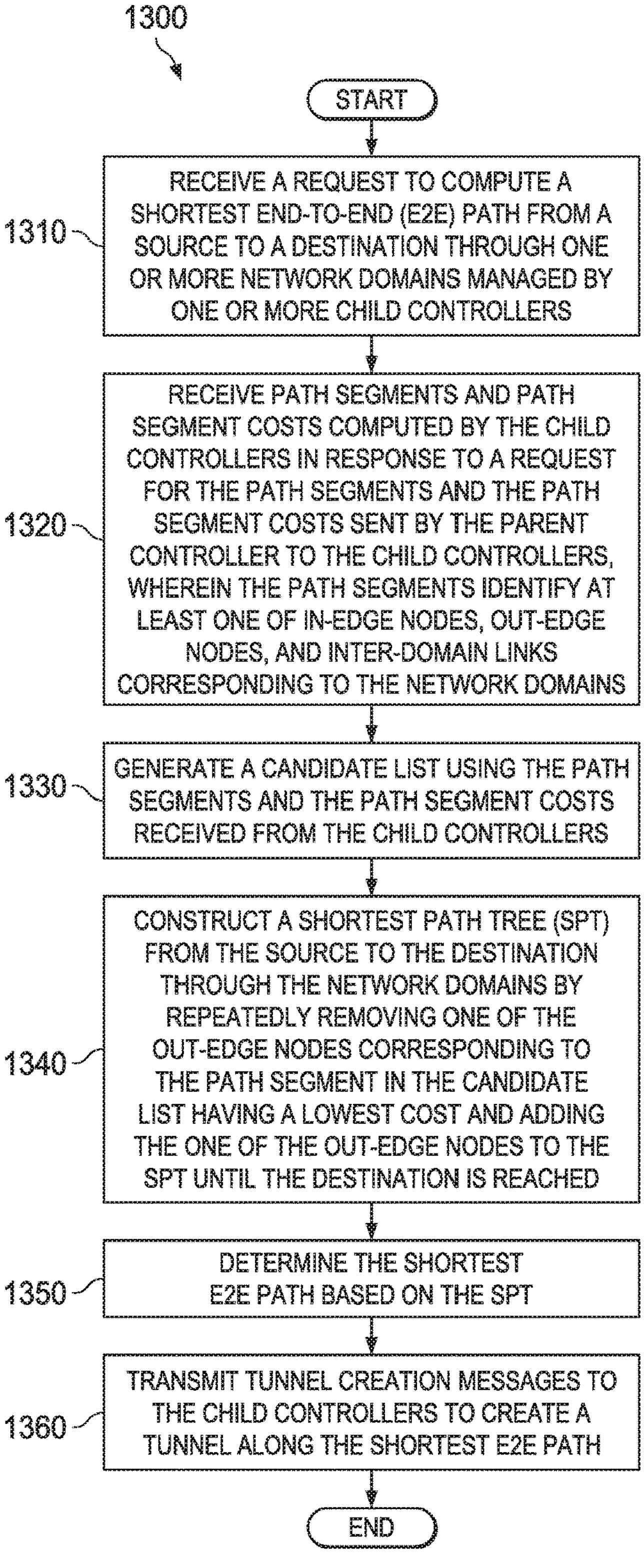
1300
START
1310
RECEIVE A REQUEST TO COMPUTE A SHORTEST END-TO-END (E2E) PATH FROM A SOURCE TO A DESTINATION THROUGH ONE OR MORE NETWORK DOMAINS MANAGED BY ONE OR MORE CHILD CONTROLLERS
1320
RECEIVE PATH SEGMENTS AND PATH SEGMENT COSTS COMPUTED BY THE CHILD CONTROLLERS IN RESPONSE TO A REQUEST FOR THE PATH SEGMENTS AND THE PATH SEGMENT COSTS SENT BY THE PARENT CONTROLLER TO THE CHILD CONTROLLERS, WHEREIN THE PATH SEGMENTS IDENTIFY AT LEAST ONE OF IN-EDGE NODES, OUT-EDGE NODES, AND INTER-DOMAIN LINKS CORRESPONDING TO THE NETWORK DOMAINS
1330
GENERATE A CANDIDATE LIST USING THE PATH SEGMENTS AND THE PATH SEGMENT COSTS RECEIVED FROM THE CHILD CONTROLLERS
1340
CONSTRUCT A SHORTEST PATH TREE (SPT) FROM THE SOURCE TO THE DESTINATION THROUGH THE NETWORK DOMAINS BY REPEATEDLY REMOVING ONE OF THE OUT-EDGE NODES CORRESPONDING TO THE PATH SEGMENT IN THE CANDIDATE LIST HAVING A LOWEST COST AND ADDING THE ONE OF THE OUT-EDGE NODES TO THE SPT UNTIL THE DESTINATION IS REACHED
1350
DETERMINE THE SHORTEST E2E PATH BASED ON THE SPT
1360
TRANSMIT TUNNEL CREATION MESSAGES TO THE CHILD CONTROLLERS TO CREATE A TUNNEL ALONG THE SHORTEST E2E PATH
END

FIG. 13

END-TO-END (E2E) TUNNEL BASED ON SHORTEST POINT-TO-POINT (P2P) PATH COMPUTATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. provisional patent application No. 62/263,925 filed Dec. 7, 2015 by Huaimo Chen and titled "System and Method for Creating End-to-End Tunnel," which is incorporated by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not applicable.

REFERENCE TO A MICROFICHE APPENDIX

Not applicable.

BACKGROUND

Telecommunications networks connect hosts to allow data communication between various geographically distant locations. Path computation for creating an E2E tunnel between hosts may be performed by a parent controller. The parent controller manages a number of child controllers through a hierarchical configuration. The child controllers implement the path computations received from the parent controller using network nodes within the domain or domains that the child controllers manage. However, path computation in large, multi-domain, multi-region, and/or multi-layer networks is complex and computationally intensive. As data usage is increasing with the proliferation of smart devices, tablet computers, network servers, and other smart devices, the demand for data to be forwarded across wireless networks, optical networks, electrical networks, and electro-optical networks is also increasing. Data providers are therefore seeking the most optimal and efficient implementation of path computation for an E2E tunnel.

SUMMARY

In an embodiment, the disclosure includes a parent controller including a receiver configured to receive a request to compute a shortest end-to-end (E2E) path from a source to a destination through one or more network domains managed by one or more child controllers, and receive path segments and path segment costs computed by the child controllers in response to a request for the path segments and the path segment costs sent by the parent controller to the child controllers, wherein the path segments identify at least one of in-edge nodes, out-edge nodes, and inter-domain links corresponding to the network domains; a processor coupled to the receiver and configured to generate a candidate list using the path segments and the path segment costs received from the child controllers, construct a shortest path tree (SPT) from the source to the destination through the network domains by repeatedly removing one of the out-edge nodes corresponding to the path segment in the candidate list having a lowest cost and adding the one of the out-edge nodes to the SPT until the destination is reached, and determine the shortest E2E path based on the SPT; and a transmitter coupled to the processor and configured to transmit tunnel creation messages to the child controllers to create a tunnel along the shortest E2E path.

In an embodiment, the processor is further configured to allocate a global tunnel identifier (ID) and a path ID for each domain for creating the tunnel along the shortest E2E path. In an embodiment, the tunnel creation messages further comprise the global tunnel ID and the path ID. In an embodiment, the path segments comprise links corresponding to the path segments. In an embodiment, the tunnel creation messages further comprise an outgoing label and a link used to create tunnel segments between the source and the destination. In an embodiment, the processor determines whether each node in one of the network domains is a destination node, a source node, one of the in-edge nodes, one of the out-edge nodes, or in a destination domain. In an embodiment, the transmitter is configured to transmit an except list to the child controllers, wherein the except list identifies nodes to which no path segments are computed. In an embodiment, the SPT is grown until the SPT includes the source and the destination.

In another embodiment, the disclosure includes a network device configured to establish an end-to-end (E2E) tunnel corresponding to an E2E path. The network device includes a transmitter configured to send a first message to a destination child controller managing a destination domain, wherein the first message includes a request to create a first segment of the E2E tunnel in the destination domain, and wherein the first message includes a first path identifier corresponding to a segment of the E2E path in the destination domain, identifies an initial node in the destination domain, and identifies a destination node in the destination domain; and a receiver operably coupled to the transmitter and configured to receive a reply message from the destination child controller in response to the first message, wherein the reply message identifies a creation status of the first segment and includes a first incoming label, wherein the first incoming label was assigned by the destination child controller to a link between the initial node in the destination domain and a next hop node in the destination domain.

In an embodiment, the reply message is received after the destination child controller has at least one of reserved resources for the first segment within the destination domain, allocated a label to each link within the first segment, and written cross connects on each node within the first segment. In an embodiment, the transmitter is configured to send a second message to an upstream child controller managing an upstream domain, wherein the second message includes a request to create a second segment of the E2E tunnel in the upstream domain. In an embodiment, the second message includes a second path identifier corresponding to a segment of the E2E path in the upstream domain, identifies an initial node in the upstream domain, and identifies a final node in the upstream domain. In an embodiment, the final node in the upstream domain and the initial node in the destination domain are a same node. In an embodiment, the receiver is configured to receive a reply message from the upstream child controller in response to the second message, wherein the reply message identifies a creation status of the second segment and includes a second incoming label, wherein the second incoming label was assigned by the upstream child controller to an inter-domain link between an out-edge node in a domain further upstream of the upstream domain and the initial node in the upstream domain. In an embodiment, the reply message is received after the upstream child controller has at least one of reserved resources for the second segment within the upstream domain, allocated a label to each link within the second segment, and written cross connects on each node within the second segment. In an embodiment, the transmitter is configured to send a third message to a source child controller managing a source domain, wherein the second message includes a request to create a third segment of the E2E tunnel in the source domain, wherein the third message includes a third path identifier corresponding to a segment of the E2E path in the source domain, identifies a source node in the source domain, and identifies a final node in the source domain. In an embodiment, the receiver is configured to receive a reply message from the source child controller in response to the third message, wherein the reply message indicates that the E2E tunnel was successfully established.

In a further embodiment, the disclosure includes a method implemented in a parent controller including receiving a request to compute a shortest end-to-end (E2E) path from a source to a destination through one or more network domains managed by one or more child controllers, receiving path segments and path segment costs computed by the child controllers in response to a request for the path segments and the path segment costs sent by the parent controller to the child controllers, wherein the path segments identify at least one of in-edge nodes, out-edge nodes, and inter-domain links corresponding to the network domains; generating a candidate list using the path segments and the path segment costs received from the child controllers, constructing a shortest path tree (SPT) from the source to the destination through the network domains by repeatedly removing one of the out-edge nodes corresponding to the path segment in the candidate list having a lowest cost and adding the one of the out-edge nodes to the SPT until the destination is reached, determining the shortest E2E path based on the SPT; and transmitting tunnel creation messages to the child controllers to create a tunnel along the shortest E2E path.

In an embodiment, the method further includes allocating a global tunnel identifier (ID) and a path ID for each domain for creating the tunnel along the shortest E2E path. In an embodiment, the method further includes transmitting an except list to the child controllers, wherein the except list identifies nodes to which no path segments are computed.

A method implemented in a parent controller including means for receiving a request to compute a shortest end-to-end (E2E) path from a source to a destination through one or more network domains managed by one or more child controllers; means for receiving path segments and path segment costs computed by the child controllers in response to a request for the path segments and the path segment costs sent by the parent controller to the child controllers, wherein the path segments identify at least one of in-edge nodes, out-edge nodes, and inter-domain links corresponding to the network domains; means for generating a candidate list using the path segments and the path segment costs received from the child controllers; means for constructing a shortest path tree (SPT) from the source to the destination through the network domains by repeatedly removing one of the out-edge nodes corresponding to the path segment in the candidate list having a lowest cost and adding the one of the out-edge nodes to the SPT until the destination is reached; means for determining the shortest E2E path based on the SPT; and means for transmitting tunnel creation messages to the child controllers to create a tunnel along the shortest E2E path.

For the purpose of clarity, any one of the foregoing embodiments may be combined with any one or more of the other foregoing embodiments to create a new embodiment within the scope of the present disclosure.

These and other features will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of this disclosure, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description, wherein like reference numerals represent like parts.

FIG. **1** is a schematic diagram of a path computation system according to an embodiment of the disclosure.

FIG. **2** is a schematic diagram of a path computation system according to an embodiment of the disclosure.

FIGS. **3**A-**3**B are a protocol diagram and a schematic diagram collectively illustrating steps for computing that portion of the shortest E2E P2P path passing through a first domain of the path computation system of FIG. **2** according to an embodiment of the disclosure.

FIGS. **4**A-**4**B are a protocol diagram and a schematic diagram collectively illustrating steps for computing that portion of the shortest E2E P2P path extending over inter-domain links between first and second domains of the path computation system of FIG. **2** according to an embodiment of the disclosure.

FIGS. **5**A-**5**B are a protocol diagram and a schematic diagram collectively illustrating steps for computing that portion of the shortest E2E P2P path within the second domain of the path computation system of FIG. **2** according to an embodiment of the disclosure.

FIGS. **6**A-**6**B are a protocol diagram and a schematic diagram collectively illustrating steps for computing that portion of the shortest E2E P2P path within a fourth domain of the path computation system of FIG. **2** according to an embodiment of the disclosure.

FIGS. **7**A-**7**B are a protocol diagram and a schematic diagram collectively illustrating steps for continuing to seek the shortest E2E P2P through the path computation system of FIG. **2** according to an embodiment of the disclosure.

FIG. **8** is a schematic diagram illustrating shortest point-to-multipoint (P2MP) paths computation in the path computation system in FIG. **2** according to an embodiment of the disclosure.

FIGS. **9**A-**9**B are a protocol diagram and a schematic diagram collectively illustrating steps for creating that portion of the E2E tunnel passing through the fourth domain of the path computation system of FIG. **2** according to an embodiment of the disclosure.

FIGS. **10**A-**10**B are a protocol diagram and a schematic diagram collectively illustrating steps for creating that portion of the E2E tunnel over inter-domain link from node F to node G and extending node G to node P in the fourth domain of the path computation system of FIG. **2** according to an embodiment of the disclosure.

FIGS. **11**A-**11**B are a protocol diagram and a schematic diagram collectively illustrating steps for creating that portion of the E2E tunnel within first domain of the path computation system of FIG. **2** according to an embodiment of the disclosure.

FIG. **12** is a schematic diagram of an apparatus configured to implement one or more of the methods disclosed herein according to an embodiment of the disclosure.

FIG. **13** is a flowchart of a method of creating an E2E tunnel along shortest E2E P2P path according to an embodiment of the disclosure.

DETAILED DESCRIPTION

It should be understood at the outset that, although illustrative implementations of one or more embodiments are provided below, the disclosed systems and/or methods may be implemented using any number of techniques, whether currently known or in existence. The disclosure should in no way be limited to the illustrative implementations, drawings, and techniques illustrated below, including the exemplary designs and implementations illustrated and described herein, but may be modified within the scope of the appended claims along with their full scope of equivalents.

Telecommunication network providers may perform network management through a variety of approaches. One approach establishes E2E tunnels in hierarchical environments to provide reliable and secure data communication. However, this approach include drawbacks, such as complex system communication among its components (e.g., inaccuracies in network related information or summary), higher computation capability requirement (e.g., parsing of inaccurate summary or topology information), and dependence on resource reservation protocol—traffic engineering (RSVP-TE) due to high traffic overhead. Therefore, the telecommunication industry seeks to optimize data communication by improving approaches for establishing E2E tunnels.

Disclosed herein are various embodiments for determining a shortest E2E P2P path used in creating an E2E tunnel from a source to a destination that satisfies a set of constraints given for the tunnel. By way of example, a parent controller receives a request to compute a E2E P2P path and establish an E2E tunnel along that path. The parent controller manages a number of child controllers, each of which manages one or more domains. The parent controller requests child controllers to compute path segments (e.g., between nodes in its domain, or from the edge node of one domain to the edge node of an adjacent domain). The parent controller builds a shortest path tree (SPT) from a candidate list of the path segments to generate the E2E P2P path. Once the E2E P2P path is determined, the parent controller establishes the E2E tunnel along the E2E P2P path. In other words, centralized and distributed computations are combined to find a shortest E2E P2P path and create the E2E tunnel along the shortest E2E P2P path. The shortest E2E P2P path for an E2E tunnel approach is described in Huaimo Chen, et al, "PCE Hierarchical SDNs," Mar. 18, 2016, which is incorporated by reference. By using the presently disclosed solution, the efficiency of network resource usage is increased and a large network with multiple domains is more effectively controlled. Furthermore, the present disclosure provides a solution for obtaining the shortest E2E P2P path crossing domains and creating the E2E tunnel along the shortest E2E P2P path for optimal data communication. Using the disclosed system, no summary of domains is sent from the child controller to the parent controller. Moreover, the parent controller computes the E2E P2P path with assistance from the child controllers using accurate topology and, therefore, the computed path is optimal. In addition, the tunnel is created without using RSVP-TE.

FIG. **1** is a schematic diagram of a path computation system **100** according to an embodiment of the disclosure. The system **100** comprises a parent controller **110**, a number of child controllers **120**, and a number of domains **130**.

The parent controller **110** is operably coupled the child controllers **120**. As such, the patent controller **120** is configured to manage the child controllers **120**. The parent controller **110** is configured to compute an E2E P2P path across the plurality of domains **130** in conjunction with the plurality of child controllers **120**.

Each of the child controllers **120** is configured to compute path segments within its respective network domain **130** and/or path segments from an edge node of its domain to an edge node of a neighboring domain (e.g., from a node F in domain **1 130** to node H in domain **3 130** in FIG. **2**). While child controllers **1**, **2**, **3**, and n **120** are shown in FIG. **1**, it is understood that the path computation system **100** may include any number of the child controllers **120** in practical applications.

The child controllers **120** are configured to exchange information regarding the path segments with the parent controller **110**. By way of example, the child controller **1 120** is configured to compute path segments traversing the domain **1 130** between specified edge nodes and to return data to the parent controller **110** indicating the addresses of the edge nodes and routing costs for the path segments in the domain **1 130** without communicating the internal topology or internal constraints of the domain **1 130**. The child controllers **1**-*n* **120** may also update the parent controller **110** regarding topology changes that affect the edge nodes, inter-domain links, and/or computed path segment constraints. The child controllers **1**-*n* **120** may also allocate and maintain routing tunnels and/or backup tunnels to transmit traffic along a portion of a path traversing the corresponding domains **1**-*n* **130**.

In an embodiment, each of the child controllers **1**-*n* **120** maintains a topology database, a TE database, a forwarding information base (FIB), and/or other data structures to track the topology of the domains **1**-*n* **130** under their control. For example, the topology may include a mapping of the connectivity of nodes and links in the domains **1**-*n* **130**, current traffic state, access point state, inter-domain link state, and any other suitable network related information. In an embodiment, a child controller **120** may control more than one of the domains **1**-*n* **130**.

The domains **1**-*n* **130** are a group of interconnected hardware and/or software devices administered by common/shared procedures, for example, common addressing schemes, security procedures. The domains **1**-*n* **130** are connected by inter-domain links, which are depicted as solid lines in FIG. **2**, for example. An inter-domain link is any link that couples two domains via one or more edge nodes. Data may be routed between domains using the inter-domain links.

Tunnels routed over a domain **130** may satisfy various constraints, depending on the nodes and links used. Constraints for an optical domain, such as a dense wavelength division multiplexing (DWDM), may include minimum chromatic dispersion, optical crosstalk, polarization impairments, optical transmitter tuning ranges such as color constraints, directional wavelength assignment constraints, optical signal to noise ratio, quality (Q) factor of optical receivers, optical cross connect requirements in specified nodes, available wavelengths, and any other optical domain constraints. Constraints for an electrical system may include electrical crosstalk, electrical signal to noise ratio requirements, and any other electrical domain constraints. Domains **130** may also comprise policy based constraints such as required quality of service (QoS), traffic priority, bandwidth requirements, and routing cost requirements. The domains **130** comprise edge nodes configured to act as access points to the domains **1**-*n* **130**. Traffic entering or leaving each of the domains **1**-*n* **130** passes through the edge nodes via inter-domain links. Edge nodes comprise internet protocol

(IP), media access control (MAC) and/or virtual addresses that can be accessed from outside of the domains **1**-*n* **130**. The edge nodes also provide security (e.g., firewalls) for each of the domains **1**-*n* **130**. Further, some domains **130** may comprise virtual extensible networks (VxNs) or virtual machines (VMs) that operate as software on hardware and emulate hardware networks.

FIG. **2** is a schematic diagram of a path computation system **200** according to an embodiment of the disclosure. The system **200** is similar to the system **100**. The system **200** comprises a parent controller **210**, child controllers **1-4 220**, domains **1-4 230** and nodes A-H and J-Z (i.e., edge nodes or access nodes). As shown in FIG. **2**, each of the domains **230** contains a plurality of nodes (e.g., routers, switches, bridges, servers, etc.). The nodes may be any network device configured to transport data or information within or through the path computation system **200**. As shown, the domain **1 230** comprises nodes A, B, C, D, E, and F, the domain **2 230** comprises nodes G, H, J, K, L, M, N, O, P, and Q, the domain **3 230** comprises nodes N, O, R, S, T, and U, and the domain **4 230** comprises nodes P, Q, V, W, X, Y, and Z. While the nodes such as nodes A, E, and F are edge nodes for domain **1 230**, the domains **230** may include one or more intermediate nodes (e.g., node C in domain **1 230** or node K in domain **2 230**) and links connecting the edge and intermediate nodes to each other. The links may include electrical, optical, and/or electro-optical wired connections or wireless connections, depending on the embodiment.

Depending on their position within the domain, the edge nodes may be referred to as an in-edge node or an out-edge node. An in-edge node is the node from which a path segment to another node in the same domain is computed. In other words, the in-edge node is the node at the beginning of the path segment. For example, in an E2E tunnel from node A (i.e., a source node) to node Z (i.e., a destination node), node A is an in-edge node of domain **1 230** for the path segment from node A to node F and the path segment from node A to node E.

An out-edge node is the node to which a path segment from another node in the same domain is computed, or the node to which a path segment from another node in a different domain is computed over an inter-domain link. In other words, the out-edge node is the node at the end of the path segment. For example, in an E2E tunnel from node A to node Z, node F is an out-edge node of domain **1 230** for the path segment from node A to node F. A node may function as both an in-edge node and an out-edge node in various circumstances. For example, in an E2E tunnel from node A to node Z, node P is an out-edge node of domain **2 230** for the path segment from node G to node P and an in-edge node of domain **4 230** for the path segments from node P to nodes Q, Y, and Z.

The system **200** further illustrates path segments computed by the child controllers **220** for the E2E tunnel from node A to node Z. The path segments are depicted by either solid arrows or dashed arrows. As will be more fully described below, the path segments depicted by solid arrows represent path segments computed and then selected for use in the E2E P2P path because, for example, the paths from the source to the out-edge nodes of the path segments had the lowest cost. The path segments depicted by dashed arrows represent path segments that were computed but not selected for use in the E2E P2P path because, for example, the paths from the source to the out-edge nodes of the path segments had a higher cost relative to other computed path segments. As shown, the solid arrows collectively form the E2E P2P path used to create the E2E tunnel from node A to node Z.

In an embodiment, a parameter other than cost may be used in the selection of path segments.

The process of computing and selecting path segments based on, for example, cost to establish the E2E P2P path used to create the E2E tunnel from node A to node Z in FIG. **2** is collectively illustrated in FIGS. **3**A-**3**B, **4**A-**4**B, **5**A-**5**B, **6**A-**6**B, and **7**A-**7**B as will be described more fully below.

FIG. **3**A is a protocol diagram **300**A illustrating steps for computing that portion of the shortest E2E P2P path passing through domain **1 230** of the path computation system of FIG. **2** according to an embodiment of the disclosure. FIG. **3**A further depicts the growth of the SPT, as will be more fully described below. FIG. **3**A includes a parent controller **210** and a child controller **1 220**. The parent controller **210** and the child controller **1 220** in FIG. **3**A are similar to the parent controller **210** and the child controller **1 220** in FIG. **2**.

The process depicted by the protocol diagram **300**A begins after the parent controller **210** receives a request for creating an E2E tunnel extending from node A to node Z. While not shown, the request may come from, for example, a client or a network administrator. In step **302**, the parent controller **210** sends a message to the child controller **1 220** with an instruction to compute a shortest path segment from the in-edge node A (e.g., the source node) to each of the out-edge nodes (e.g., node E and node F) of domain **1 230** satisfying the constraints for the E2E tunnel. In response to the instruction, the child controller **1 220** determines the path segments and the corresponding costs between the in-edge node and the out-edge nodes. FIG. **3**B illustrates a path computation system **300**B where, for example, the child controller **1 220** calculated a path segment extending from node A to node E with cost of 8 and another path segment extending from node A to node F with cost of 3.

Once the path segments and associated costs are determined, the child controller **1 220** provides the path and cost information to the parent controller **210** as links in step **304**. In an embodiment, the details of each path segment are hidden from the parent controller **210** and stored under a tunnel identification (ID) and a path ID (e.g., for example, a tunnel ID of **1015** and a path ID of **103**) allocated by the parent controller **210**. For example, the child controller **1 220** reports the tunnel ID, the path ID, the path segment from node A to F with a cost of 3, and the path segment from node A to E with a cost of 8 to the parent controller **210**. However, the child controller **1 220** withholds the identity of the intermediate nodes (e.g., nodes B, D, C) within domain **1 230** from the parent controller **210**.

The parent controller **210** adds each link corresponding to the path segment and cost to a candidate list. For example, after step **304** in FIG. **3**A the candidate list includes a link that corresponds to a path segment from node A to node F with a cost of 3 and a link that corresponds to the path segment from node A to node E with a cost of 8. By way of example, the candidate list may be represented as: A→F with cost **3**, and A→E with cost **8**.

Because the path segment from node A to node F has a lower cost than the path segment from node A to node E, the parent controller **210** removes the out-edge node F from the candidate list and adds node F to the SPT as shown in FIG. **3**A. As such, the SPT is grown from source node A to an SPT having a branch extending from source node A to node F with a cost of 3.

As shown in FIG. **3**B, the path segment that was selected (e.g., from node A to node F) is shown by a solid arrow, while the path segment that was not selected (e.g., from node A to node E) is shown by a dashed arrow. In addition, node

F is designated with a star to indicate that node F was added to the SPT. In an embodiment, the parent controller **210** maintains an except list (a.k.a., an exception list) that includes each of the nodes to which no path segment is computed. The except list may be transmitted to child controllers along with other messages.

FIG. **4**A is a protocol diagram **400**A illustrating steps for computing that portion of the shortest E2E P2P path extending over inter-domain links between domain **1 230** and domain **2 230** of the path computation system of FIG. **2** according to an embodiment of the disclosure. FIG. **4**A further depicts the growth of the SPT, as will be more fully described below. FIG. **4**A includes a parent controller **210** and a child controller **1 220**. The parent controller **210** and the child controller **1 220** in FIG. **4**A are similar to the parent controller **210** and the child controller **1 220** in FIG. **2**.

In an embodiment, the process depicted by the protocol diagram **400**A begins after the process in FIG. **3**A has been completed. In step **402**, the parent controller **210** sends a message to the child controller **1 220** with an instruction to compute a shortest path segment from the in-edge node F of domain **1 230** to each of the out-edge nodes (e.g., node G and node H) of domain **2 230** satisfying the constraints for the E2E tunnel. In response to the instruction, the child controller **1 220** determines the path segments and the corresponding costs between the in-edge node and the out-edge nodes. FIG. **4**B illustrates a path computation system **400**B where, for example, the child controller **1 220** calculated a path segment extending from node F to node G with cost of 1 and another path segment extending from node F to node H with cost of 6.

Once the path segments and associated costs are determined, the child controller **1 220** provides the path and cost information to the parent controller **210** as links in step **404**. In an embodiment, the details of each path segment are hidden from the parent controller **210** and stored under a tunnel ID and a path ID allocated by the parent controller **210**. For example, the child controller **1 220** reports the tunnel ID, the path ID, the path segment from node F to node G with a cost of 1, and the path segment from node F to node H with a cost of 6 to the parent controller **210**.

The parent controller **210** adds each link corresponding to the path segment and cost to the existing candidate list. For example, after step **404** in FIG. **4**A the candidate list includes a link that corresponds to the path segment from node A to node E with a cost of 8 (previously calculated), a path segment from node A, to node F, to node G with a cost of 4 (e.g., 3+1), and a link that corresponds to the path segment from node A, to node F, to node H with a cost of 9 (e.g., 3+6). By way of example, the candidate list may be represented as: A→E with cost **8**, A→F→G with cost **4**, and A→F→H with cost **9**.

Because the path segment associated with node G has a lower cost than the other path segments in the candidate list, the parent controller **210** removes the out-edge node G from the candidate list and adds node G to the SPT as shown in FIG. **4**A. As such, the SPT is grown to include a branch extending from node F to node G with a cost of 1.

As shown in FIG. **4**B, the path segment that was selected (e.g., from node F to node G) is shown by a solid arrow, while the other path segments that were not selected are shown by a dashed arrow. In addition, node G is designated with a star to indicate that node G was added to the SPT.

In an embodiment, instead of performing the process described with regard to FIGS. **4**A-**4**B after performing the process described with regard to FIGS. **3**A-**3**B, the parent controller **210** may request that child controller **1 220** compute path segments from node A in domain **1 230** to node G in domain **2 230**. In other words, in an embodiment the parent controller **210** requests one or more of the child controllers **220** to compute path segments from the in-edge node (e.g., node A) of one domain to one or more of the in-edge nodes (e.g., node G) of an adjacent domain. In other words, two processes are combined into one in such an embodiment. In addition, in an embodiment node G is considered to be an in-edge node, but not considered to be an ingress node. This is because, for example, node G is not an ingress node relative to the entire E2E P2P path. In other words, node G is in the middle of the E2E P2P path and, as such, is not considered an ingress node despite being on the edge of domain **2 230**.

FIG. **5**A is a protocol diagram **500**A illustrating steps for computing that portion of the shortest E2E P2P path within domain **2 230** of the path computation system of FIG. **2** according to an embodiment of the disclosure. FIG. **5**A further depicts the growth of the SPT, as will be more fully described below. FIG. **5**A includes a parent controller **210** and a child controller **2 220**. The parent controller **210** and the child controller **2 220** in FIG. **5**A are similar to the parent controller **210** and the child controller **2 220** in FIG. **2**.

In an embodiment, the process depicted by the protocol diagram **500**A begins after the process in FIG. **4**A has been completed. In step **502**, the parent controller **210** sends a message to the child controller **2 220** with an instruction to compute a shortest path segment from the in-edge node G of domain **2 230** to each of the out-edge nodes (e.g., node N, node O, node P, node Q, and node H) of domain **2 230** satisfying the constraints for the E2E tunnel. In response to the instruction, the child controller **2 220** determines the path segments and the corresponding costs between the in-edge nodes and the out-edge nodes. FIG. **5**B illustrates a path computation system **500**B where, for example, the child controller **2 220** calculated a path segment extending from node G to node N with cost of 9, a path segment extending from node G to node O with cost of 8, a path segment extending from node G to node P with cost of 2, and a path segment extending from node G to node Q with cost of 6, and a path segment extending from node G to node H with cost of 5.

Once the path segments and associated costs are determined, the child controller **2 220** provides the path and cost information to the parent controller **210** as links in step **504**. In an embodiment, the details of each path segment are hidden from the parent controller **210** and stored under a tunnel ID and a path ID allocated by the parent controller **210**. For example, the child controller **2 220** reports the tunnel ID, the path ID, the path segment from node G to node N with a cost of 9, the path segment from node G to node O with a cost of 8, the path segment from node G to node P with a cost of 2, the path segment from node G to node Q with a cost of 6, and the path segment from node G to node H with a cost of 5 to the parent controller **210**.

The parent controller **210** adds each link corresponding to the path segment and cost to the existing candidate list. For example, after step **504** in FIG. **5**A the candidate list includes a link that corresponds to the path segment from node A to node E with a cost of 8 (previously calculated), a link that corresponds to the path segment from node A, to node F, to node H with a cost of 9 (previously calculated), a path segment from node A, to node F, to node G, to node N with a cost of 13, a path segment from node A, to node F, to node G, to node O with a cost of 12, a path segment from node A, to node F, to node G, to node P with a cost of 6, and a path segment from node A, to node F, to node G, to node Q with a cost of 10. By way of example, the candidate list may be represented as: A→E with cost **8**, A→F→H with cost **9**, A→F→G→N with cost **13**, A→F→G→O with cost **12**, A→F→G→P with cost **6**, and A→F→G→Q with cost **10**.

Because the path segment associated with node P has a lower cost than the other path segments in the candidate list, the parent controller **210** removes the out-edge node P from the candidate list and adds node P to the SPT as shown in FIG. **5**A. As such, the SPT is grown to include a branch extending from node G to node P with a cost of 2.

As shown in FIG. **5**B, the path segment that was selected (e.g., from node G to node P) is shown by a solid arrow, while the other path segments that were not selected are shown by dashed arrows. In addition, node P is designated with a star to indicate that node P was added to the SPT.

FIG. **6**A is a protocol diagram **600**A illustrating steps for computing that portion of the shortest E2E P2P path within domain **4 230** of the path computation system of FIG. **2** according to an embodiment of the disclosure. FIG. **6**A further depicts the growth of the SPT, as will be more fully described below. FIG. **6**A includes a parent controller **210** and a child controller **4 220**. The parent controller **210** and the child controller **4 220** in FIG. **6**A are similar to the parent controller **210** and the child controller **4 220** in FIG. **2**.

In an embodiment, the process depicted by the protocol diagram **600**A begins after the process in FIG. **5**A has been completed. In step **602**, the parent controller **210** sends a message to the child controller **4 220** with an instruction to compute a shortest path segment from the node P, which is an in-edge node of domain **4 230** and out-edge node of domain **2 230**, to each of the out-edge nodes (e.g., node Z, node Y, and node Q) of domain **4 230** satisfying the constraints for the E2E tunnel. In response to the instruction, the child controller **4 220** determines the path segments and the corresponding costs between the in-edge node (e.g., node P) and the out-edge nodes. FIG. **6**B illustrates a path computation system **600**B where, for example, the child controller **4 220** calculated a path segment extending from node P to node Z with cost of 3, a path segment extending from node P to node Y with cost of 9, and a path segment extending from node P to node Q with cost of 4. It should be understood that while other paths which associated costs might be calculated, only these are discussed for the sake of brevity.

Once the path segments and associated costs are determined, the child controller **4 220** provides the path and cost information to the parent controller **210** as links in step **604**. In an embodiment, the details of each path segment are hidden from the parent controller **210** and stored under a tunnel ID and a path ID allocated by the parent controller **210**. For example, the child controller **4 220** reports the tunnel ID, the path ID, the path segment from node P to node Z with a cost of 3, the path segment from node P to node Y with a cost of 9, and the path segment from node P to node Q with a cost of 4 to the parent controller **210**.

The parent controller **210** adds each link corresponding to the path segment and cost to the existing candidate list. For example, after step **604** in FIG. **6**A the candidate list includes a link that corresponds to the path segment from node A to node E with a cost of 8 (previously calculated), a link that corresponds to the path segment from node A, to node F, to node H with a cost of 9 (previously calculated), a path segment from node A, to node F, to node G, to node N with a cost of 13 (previously calculated), a path segment from node A, to node F, to node G, to node O with a cost of 12 (previously calculated), a path segment from node A, to node F, to node G, to node Q with a cost of 10 (previously calculated), a path segment from node A, to node F, to node G, to node P, to node Z with a cost of 9, and a path segment from node A, to node F, to node G, to node P, to node Y with a cost of 15. By way of example, the candidate list may be represented as: A→E with cost **8**, A→F→H with cost **9**, A→F→G→N with cost **13**, A→F→G→O with cost **12**, A→F→G→Q with cost **10**, A→F→G→P→Z with cost **9**, and A→F→G→P→Y with cost **15**.

Because the path segment associated with node E has a lower cost than the other path segments in the candidate list, the parent controller **210** removes the out-edge node E from the candidate list and adds node E to the SPT as shown in FIG. **6**A. As such, the SPT is grown to include a branch extending from node A to node E with a cost of 8.

As shown in FIG. **6**B, the path segment that was selected (e.g., from node A to node E) is shown by a solid arrow (since no other lower cost path to node E exists). In addition, node E is designated with a star to indicate that node E was added to the SPT.

FIG. **7**A is a protocol diagram **700**A illustrating steps for continuing to seek the shortest E2E P2P through the path computation system of FIG. **2** according to an embodiment of the disclosure. FIG. **7**A further depicts the growth of the SPT, as will be more fully described below. FIG. **7**A includes a parent controller **210** and a child controller **1 220**. The parent controller **210** and the child controller **1 220** in FIG. **7**A are similar to the parent controller **210** and the child controller **1 220** in FIG. **2**.

In an embodiment, the process depicted by the protocol diagram **700**A begins after the process in FIG. **6**A has been completed. In step **702**, the parent controller **210** sends a message to the child controller **1 220** with an instruction to compute a shortest path segment from the in-edge node E of domain **1 230** to the out-edge node (e.g., node H) of domain **2 230** satisfying the constraints for the E2E tunnel. In response to the instruction, the child controller **1 220** determines the path segment and the corresponding cost between the in-edge node and the out-edge node. FIG. **7**B illustrates a path computation system **700**B where, for example, the child controller **1 220** calculated a path segment extending from node E to node H with a cost of 3.

Once the path segment and associated cost is determined, the child controller **1 220** provides the path and cost information to the parent controller **210** as a link in step **704**. In an embodiment, the details of the path segment are hidden from the parent controller **210** and stored under a tunnel ID and a path ID allocated by the parent controller **210**. For example, the child controller **1 220** reports the tunnel ID, the path ID, the path segment from node E to H with a cost of 3 to the parent controller **210**.

The parent controller **210** adds the link corresponding to the path segment and cost to the existing candidate list. For example, after step **704** in FIG. **7**A the candidate list includes a link that corresponds to the path segment from node A, to node F, to node H with a cost of 9 (previously calculated), a path segment from node A, to node F, to node G, to node N with a cost of 13 (previously calculated), a path segment from node A, to node F, to node G, to node O with a cost of 12 (previously calculated), a path segment from node A, to node F, to node G, to node Q with a cost of 10 (previously calculated), a path segment from node A, to node F, to node G, to node P, to node Z with a cost of 9, and a path segment from node A, to node F, to node G, to node P, to node Y with a cost of 15. By way of example, the candidate list may be represented as: A→F→H with cost **9**, A→F→G→N with cost **13**, A→F→G→O with cost **12**, A→F→G→Q with cost **10**, A→F→G→P→Z with cost **9**, and A→F→G→P→Y with cost **15**.

Because the path segment associated with node Z has a cost that is equal to or less than the other path segments in the candidate list, the parent controller **210** removes the out-edge node Z from the candidate list and adds node Z to the SPT as shown in FIG. **7**A. As such, the SPT is grown to include a branch extending from node P to node Z with a cost of 3. Because node Z is the destination node, the lowest cost path from A to Z has been found and a corresponding E2E tunnel may be established along the path.

As shown in FIG. **7**B, the path segment that was selected (e.g., from node P to node Z) is shown by a solid arrow, while the other path segments that were not selected are shown by dashed arrows. In addition, node Z is designated with a star to indicate that node Z was added to the SPT.

FIG. **8** is a schematic diagram **800** illustrating a shortest point-to-multipoint (P2MP) path computation in path computation system **200** of FIG. **2** according to an embodiment of the disclosure. FIG. **8** includes a parent controller **210**, child controllers **1-4 220**, domains **1-4 230** and nodes A-H and J-Z. The parent controller **210** and the child controllers **220** in FIG. **8** are similar to the parent controller **210** and the child controllers **220** in FIG. **2**, and the domains **230** in FIG. **8** are similar to the domains **230** in FIG. **2**. In an embodiment, the shortest P2MP path computation comprises a number of the E2E P2P path computations. In other words, the E2E P2P path computation concept may be extended to find a shortest E2E P2MP path. For example, FIG. **8** comprises a number of shortest E2E P2P paths extending from node A (e.g., the source node) to nodes T, U, and Z (e.g., the destination nodes) as shown in FIG. **8**. The process of computing and selecting the P2MP paths based on, for example, cost is similar to the process described above in FIGS. **3**A-**3**B, **4**A-**4**B, **5**A-**5**B, **6**A-**6**B, and **7**A-**7**B to establish the E2E P2P path for the E2E tunnel. In an embodiment, the shortest P2MP path computation grows its SPT until all the destination nodes are on the SPT as opposed to E2E P2P path computation, which grows the SPT to a single destination node.

Once the shortest E2E P2P path or the shortest E2E P2MP paths are determined in the manner noted above, the parent controller **210** creates the E2E tunnel. For the sake of brevity, only the manner in which the E2E tunnel along the E2E P2P path will be discussed in detail. Even so, those skilled in the art will appreciate the manner in which the E2E tunnel along the E2E P2MP path is created upon reviewing this disclosure.

The parent controller **210** creates the E2E tunnel by instructing the child controllers **220** to establish the E2E tunnel along the shortest E2E P2P path in a reverse direction from node Z to node A. For example, the parent controller **210** instructs the child controller **4 220** (e.g., the destination controller) to create a tunnel segment in the domain **4 230** (e.g., the destination domain), then instructs the child controller **2 220** to create the tunnel segment in the domain **2 230**, and so on. A detailed process of creating the E2E tunnel extending from node A to node Z in FIG. **2** is collectively illustrated in FIGS. **9**A-**9**B, **10**A-**10**B, and **11**A-**11**B and will be described more fully below.

FIG. **9**A is a protocol diagram **900**A illustrating steps for creating that portion of the E2E tunnel passing through domain **4 230** of the path computation system of FIG. **2** according to an embodiment of the disclosure. FIG. **9**A includes a parent controller **210** and a child controller **4 220**. The parent controller **210** and the child controller **4 220** in FIG. **9**A are similar to the parent controller **210** and the child controller **4 220** in FIG. **2**.

The process depicted by the protocol diagram **900**A begins after the parent controller **210** determines that the SPT has grown to include node Z (e.g., the destination node). In step **902**, the parent controller **210** sends a message to the child controller **4 220** with an instruction to create a tunnel segment in domain **4 230** from the node P to the node Z. In an embodiment, the parent controller **210** allocates a global tunnel ID and a path ID corresponding to the domain and includes the global tunnel ID and the path ID in the message to the child controller **4 220**. In response to the instruction, the child controller **4 220** creates the tunnel segment by reserving resources (e.g., link bandwidth), allocating incoming labels, and writing cross connects on every node along the tunnel segment. FIG. **9**B illustrates a path computation system **900**B where, for example, the child controller **4 220** created a tunnel segment extending from node P to node Z.

By way of example as shown in FIG. **9**B, the child controller **4 220** reserves the resources on the link from P to V, the link from V to X, and the link from X to Z. In addition, the child controller **4 220** allocates incoming label **9** for the node Z and the link from X to Z, incoming label **7** for the node X and the link from V to X, and incoming label **5** for the node V and the link P to V. The child controller **4 220** also writes cross connect in-label **5** switching to out-label **7** on the node V, cross connect in-label **7** switching to out-label **9** on the node X, and a pop in-label **9** on the node Z.

Returning to FIG. **9**A, once the tunnel segment in the domain is created, the child controller **4 220** provides the outgoing label (e.g., **5**) of node P, the link P→V, and the tunnel segment creation status to the parent controller **210** in step **904**. The outgoing label of node P is the incoming label of the next hop V of node P. In an embodiment, the parent controller **210** sends the outgoing label and the links (e.g., link P→V) to upstream or intermediate child controllers (e.g., child controller **2 220**) for creating intermediate tunnel segments.

FIG. **10**A is a protocol diagram **1000**A illustrating steps for creating that portion of the E2E tunnel over inter-domain link from node F to node G and extending node G to node P in domain **4 230** of the path computation system of FIG. **2** according to an embodiment of the disclosure. FIG. **10**A includes a parent controller **210** and a child controller **2 220**. The parent controller **210** and the child controller **2 220** in FIG. **10**A are similar to the parent controller **210** and the child controller **2 220** in FIG. **2**.

In an embodiment, the process depicted by the protocol diagram **1000**A begins after the process in FIG. **9**A has been completed. In step **1002**, the parent controller **210** sends a message to the child controller **2 220** with an instruction which includes the global tunnel ID and path ID to create a tunnel segment from node G to node P. While not shown, the message further includes creating the tunnel segment over inter-domain link from node F to node G. In response to the instruction, the child controller **2 220** creates the tunnel segment by reserving the resources, allocating incoming labels, and writing cross connects on every node along the tunnel segment. FIG. **10**B illustrates a path computation system **1000**B where, for example, the child controller **2 220** created a tunnel segment extending from node F to node P.

By way of example as shown in FIG. **10**B, the child controller **2 220** reserves the resources on every link identified by the path ID, such as link from F to G, link from G to K, and link from K to P. In addition, the child controller

2 220 allocates incoming label **8** for the node P and link from K to P, incoming label **6** for the node K and link from G to K, and incoming label **4** for the node G and link from F to G. The child controller **2 220** also writes cross connect in-label **4** switching to out-label **6** on the node G, in-label **6** switching to out-label **8** on the node K, and in-label **8** switching to out-label **5** on the node P.

Returning to FIG. **10**A, once the tunnel segment in the intermediate domain is created, the child controller **2 220** provides the outgoing label (e.g., **4**) of node F, link F→G, and the tunnel segment creation status to the parent controller **210** in step **1004**. The outgoing label of node F is the incoming label of the next hop node G of node F.

FIG. **11**A is a protocol diagram **1100**A illustrating steps for creating that portion of the E2E tunnel within domain **1 230** of the path computation system of FIG. **2** according to an embodiment of the disclosure. FIG. **11**A includes a parent controller **210** and a child controller **1 220**. The parent controller **210** and the child controller **1 220** in FIG. **11**A are similar to the parent controller **210** and the child controller **1 220** in FIG. **2**.

In an embodiment, the process depicted by the protocol diagram **1100**A begins after the process in FIG. **10**A has been completed. In step **1102**, the parent controller **210** sends a message to the child controller **1 220** with an instruction to create a tunnel segment from node A to node F in domain **1 230**. In response to the instruction, the child controller **1 220** creates the tunnel segment by reserving resources, allocating incoming labels, and writing cross connects on every node along the tunnel segment. FIG. **11**B illustrates a path computation system **1100**B where, for example, the child controller **1 220** created a tunnel segment extending from node A to node F.

By way of example as shown in FIG. **11**B, the child controller **1 220** reserves resources on every link identified by the path ID, such as link from D to F, link from B to D, and link from A to B. In addition, the child controller **1 220** allocates incoming label **18** for the node F and the link from D to F, incoming label **16** for the node D and the link from B to D, and incoming label **15** for the node B and link from A to B. The child controller **1 220** writes the cross connect push label **15** on the node A, in-label **15** switching to out-label **16** on the node B, in-label **16** switching to out-label **18** on the node D, and in-label **18** switching to out-label **4** on the node F.

Returning to FIG. **11**A, once the tunnel segment is created, the child controller **1 220** provides the tunnel segment creation status (e.g., success) in domain **1 230** back to the parent controller **210**. As such, the E2E tunnel from the node A to the node Z is created successfully after the parent controller **210** receives the reply with success from the child controller **1 220**. Therefore, by using the shortest P2P path computation to establish the E2E tunnel, data communication achieves better efficiency (e.g., routing cost), reduces complex communication among components, and increases network resource usage.

FIG. **12** is a schematic diagram of an apparatus **1200** configured to implement one or more of the methods disclosed herein according to an embodiment of the disclosure. The apparatus **1200** is suitable for implementing the disclosed embodiments, for instance the system **100** or the system **200**. The apparatus **1200** comprises ingress ports **1210** and receiver units (Rx) **1220** for receiving data, a processor, logic unit, or central processing unit (CPU) **1230** to process the data, transmitter units (Tx) **1240** and egress ports **1250** for transmitting the data, and a memory **1260** for storing the data. The apparatus **1200** may also comprise optical-to-electrical (OE) components and electrical-to-optical (EO) components coupled to the ingress ports **1210**, the receiver units **1220**, the transmitter units **1240**, and the egress ports **1250** for ingress or egress of optical or electrical signals.

The processor **1230** is implemented by any suitable combination of hardware, middleware, firmware, and software. The processor **1230** may be implemented as one or more CPU chips, cores (e.g. as a multi-core processor), field-programmable gate arrays (FPGAs), application specific integrated circuits (ASICs), or digital signal processors (DSPs). The processor **1230** is in communication with the ingress ports **1210**, receiver units **1220**, transmitter units **1240**, egress ports **1250**, and memory **1260**. The processor **1230** comprises an E2E P2P path computation for E2E tunnel module **1270**. The E2E P2P path computation for E2E tunnel module **1270** implements the disclosed embodiments. For instance, the inclusion of the E2E P2P path for E2E tunnel module **1270** provides a substantial improvement to the spectrum efficiency and systems complexity. The E2E P2P path for E2E tunnel module **1270** further improves the functionality of the apparatus **1200** and effects a transformation of the apparatus **1200** to a different state. Alternatively, the memory **1260** may store the shortest path computation module as instructions, and the processor **1230** executes those instructions. Further in the alternative, the apparatus **1200** comprises other means to implement the embodiments.

The memory **1260** comprises one or more disks, tape drives, or solid-state drives and may be used as an over-flow data storage device, to store programs when such programs are selected for execution, or to store instructions and data that are read during program execution. The memory **1260** may be volatile and/or non-volatile and may be read-only memory (ROM), random-access memory (RAM), ternary content-addressable memory (TCAM), or static random-access memory (SRAM).

FIG. **13** is a flowchart of a method **1300** of performing E2E tunnel creation based on the shortest E2E P2P path computation according to an embodiment of the disclosure. The method **1300** may be implemented by a network system such as the path computation system **100** and **200**, or any suitable combinations of other devices implementing the path computation system **100** and **200**. At step **1310**, the parent controller receives a request to compute a shortest E2E path from a source to a destination through one or more network domains managed by one or more child controllers. At step **1320**, the parent controller receives path segments and path segment costs computed by the child controllers in response to a request for the path segments and the path segment costs sent by the parent controller to the child controllers. In an embodiment, the path segments identify at least one of in-edge nodes, out-edge nodes, and inter-domain links corresponding to the network domains.

At step **1330**, the parent controller generates a candidate list using the path segments and the path segment costs received from the child controllers. At step **1340**, the parent controller constructs the SPT from the source to the destination through the network domains by repeatedly removing one of the out-edge nodes corresponding to the path segment in the candidate list having a lowest cost and adding the one of the out-edge nodes to the SPT until the destination is reached. Those skilled in the art will appreciate that the process of adding nodes to the SPT is more fully detailed above. For the sake of brevity, this process is not fully repeated here.

At step **1350**, the parent controller determines the shortest E2E path based on the SPT. At step **1360**, the parent controller transmits tunnel creation messages to the child controllers to create a tunnel along the shortest E2E path. Those skilled in the art will appreciate that the tunnel creation process is more fully detailed above. For the sake of brevity, this process is not fully repeated here.

A parent controller including means for receiving a request to compute a shortest end-to-end (E2E) path from a source to a destination through one or more network domains managed by one or more child controllers and for receiving path segments and path segment costs computed by the child controllers in response to a request for the path segments and the path segment costs sent by the parent controller to the child controllers, wherein the path segments identify at least one of in-edge nodes, out-edge nodes, and inter-domain links corresponding to the network domains; means for processing configured to generate a candidate list using the path segments and the path segment costs received from the child controllers, construct a shortest path tree (SPT) from the source to the destination through the network domains by repeatedly removing one of the out-edge nodes corresponding to the path segment in the candidate list having a lowest cost and adding the one of the out-edge nodes to the SPT until the destination is reached, and determine the shortest E2E path based on the SPT; and means for transmitting configured to transmit tunnel creation messages to the child controllers to create a tunnel along the shortest E2E path.

A network device configured to establish an end-to-end (E2E) tunnel corresponding to an E2E path. The network device includes means for transmitting configured to send a first message to a destination child controller managing a destination domain, wherein the first message includes a request to create a first segment of the E2E tunnel in the destination domain, and wherein the first message includes a first path identifier corresponding to a segment of the E2E path in the destination domain, identifies an initial node in the destination domain, and identifies a destination node in the destination domain; and means for receiving configured to receive a reply message from the destination child controller in response to the first message, wherein the reply message identifies a creation status of the first segment and includes a first incoming label, wherein the first incoming label was assigned by the destination child controller to a link between the initial node in the destination domain and a next hop node in the destination domain.

While several embodiments have been provided in the present disclosure, it may be understood that the disclosed systems and methods might be embodied in many other specific forms without departing from the spirit or scope of the present disclosure. The present examples are to be considered as illustrative and not restrictive, and the intention is not to be limited to the details given herein. For example, the various elements or components may be combined or integrated in another system or certain features may be omitted, or not implemented.

In addition, techniques, systems, subsystems, and methods described and illustrated in the various embodiments as discrete or separate may be combined or integrated with other systems, units, techniques, or methods without departing from the scope of the present disclosure. Other items shown or discussed as coupled or directly coupled or communicating with each other may be indirectly coupled or communicating through some interface, device, or intermediate component whether electrically, mechanically, or otherwise. Other examples of changes, substitutions, and alterations are ascertainable by one skilled in the art and may be made without departing from the spirit and scope disclosed herein.

What is claimed is:

1. A parent controller comprising:

a receiver configured to:

receive a request to compute a shortest end-to-end (E2E) path from a source to a destination through one or more network domains managed by one or more child controllers; and

receive path segments and path segment costs computed by the child controllers in response to a request for the path segments and the path segment costs sent by the parent controller to the child controllers, wherein the path segments identify at least one of in-edge nodes, out-edge nodes, and inter-domain links corresponding to the network domains;

a processor coupled to the receiver and configured to:

generate a candidate list using the path segments and the path segment costs received from the child controllers;

construct a shortest path tree (SPT) from the source to the destination through the network domains by repeatedly removing one of the out-edge nodes corresponding to the path segment in the candidate list having a lowest cost and adding the one of the out-edge nodes to the SPT until the destination is reached; and

determine the shortest E2E path based on the SPT; and

a transmitter coupled to the processor and configured to transmit tunnel creation messages to the child controllers to create a tunnel along the shortest E2E path.

2. The parent controller of claim **1**, wherein the processor is further configured to allocate a global tunnel identifier (ID) and a path ID for each network domain for creating the tunnel along the shortest E2E path.

3. The parent controller of claim **2**, wherein the tunnel creation messages further comprise the global tunnel ID and the path ID.

4. The parent controller of claim **1**, wherein the path segments comprise links corresponding to the path segments.

5. The parent controller of claim **1**, wherein the tunnel creation messages further comprise an outgoing label and a link used to create tunnel segments between the source and the destination.

6. The parent controller of claim **1**, wherein the processor determines whether each node in one of the network domains is a destination node, a source node, one of the in-edge nodes, one of the out-edge nodes, or in a destination domain.

7. The parent controller of claim **1**, wherein the transmitter is configured to transmit an except list to the child controllers, wherein the except list identifies nodes to which no path segments are computed.

8. The parent controller of claim **1**, wherein the SPT is grown until the SPT includes the source and the destination.

9. A network device configured to establish an end-to-end (E2E) tunnel corresponding to an E2E path, comprising:

a transmitter configured to send a first message to a destination child controller managing a destination domain, wherein the first message includes a request to create a first segment of the E2E tunnel in the destination domain, and wherein the first message includes a first path identifier corresponding to a segment of the E2E path in the destination domain, identifies an initial node in the destination domain, and identifies a destination node in the destination domain; and

a receiver operably coupled to the transmitter and configured to receive a reply message from the destination child controller in response to the first message, wherein the reply message identifies a creation status of the first segment and includes a first incoming label, wherein the first incoming label was assigned by the destination child controller to a link between the initial node in the destination domain and a next hop node in the destination domain.

10. The network device of claim **9**, wherein the reply message is received after the destination child controller has at least one of reserved resources for the first segment within the destination domain, allocated a label to each link within the first segment, and written cross connects on each node within the first segment.

11. The network device of claim **9**, wherein the transmitter is configured to send a second message to an upstream child controller managing an upstream domain, wherein the second message includes a request to create a second segment of the E2E tunnel in the upstream domain.

12. The network device of claim **11**, wherein the second message includes a second path identifier corresponding to a segment of the E2E path in the upstream domain, identifies an initial node in the upstream domain, and identifies a final node in the upstream domain.

13. The network device of claim **12**, wherein the final node in the upstream domain and the initial node in the destination domain are a same node.

14. The network device of claim **12**, wherein the receiver is configured to receive a reply message from the upstream child controller in response to the second message, wherein the reply message identifies a creation status of the second segment and includes a second incoming label, wherein the second incoming label was assigned by the upstream child controller to an inter-domain link between an out-edge node in a domain further upstream of the upstream domain and the initial node in the upstream domain.

15. The network device of claim **14**, wherein the reply message is received after the upstream child controller has at least one of reserved resources for the second segment within the upstream domain, allocated a label to each link within the second segment, and written cross connects on each node within the second segment.

16. The network device of claim **15**, wherein the transmitter is configured to send a third message to a source child controller managing a source domain, wherein the second message includes a request to create a third segment of the E2E tunnel in the source domain, wherein the third message includes a third path identifier corresponding to a segment of the E2E path in the source domain, identifies a source node in the source domain, and identifies a final node in the source domain.

17. The network device of claim **16**, wherein the receiver is configured to receive a reply message from the source child controller in response to the third message, wherein the reply message indicates that the E2E tunnel was successfully established.

18. A method implemented in a parent controller, comprising:

receiving a request to compute a shortest end-to-end (E2E) path from a source to a destination through one or more network domains managed by one or more child controllers;

receiving path segments and path segment costs computed by the child controllers in response to a request for the path segments and the path segment costs sent by the parent controller to the child controllers, wherein the path segments identify at least one of in-edge nodes, out-edge nodes, and inter-domain links corresponding to the network domains;

generating a candidate list using the path segments and the path segment costs received from the child controllers;

constructing a shortest path tree (SPT) from the source to the destination through the network domains by repeatedly removing one of the out-edge nodes corresponding to the path segment in the candidate list having a lowest cost and adding the one of the out-edge nodes to the SPT until the destination is reached;

determining the shortest E2E path based on the SPT; and

transmitting tunnel creation messages to the child controllers to create a tunnel along the shortest E2E path.

19. The method of claim **18**, further comprising allocating a global tunnel identifier (ID) and a path ID for each network domain for creating the tunnel along the shortest E2E path.

20. The method of claim **19**, further comprising transmitting an except list to the child controllers, wherein the except list identifies nodes to which no path segments are computed.

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